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Noise Criteria for Buildings: A Critical Review

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Noise Criteria for Buildings: A Critical Review

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ABSTRACT

A review is given of existing criteria that could be applied to rating the noise environment in dwellings, to rating noise isolation between dwellings, and to rating noise isolation from outside to inside a dwelling. It is concluded that the central problem is to select appropriate criteria for rating the interior noise environment. Once this is done, criteria for noise isolation can be derived directly and these in turn can be used to derive performance requirements for building elements, such as partitions and exterior walls.

Key words: Building acoustics; building codes; isolation; noise; noise criteria; rating scheme; sound transmission.

1. INTRODUCTION

The major function of human shelter is to provide a better environment than that to which people would otherwise be exposed. In order to enjoy the advantages of an improved environment, most people spend a large amount of their time indoors. While the majority of buildings provide adequate protection from heat and cold, wind and rain, many buildings do not provide a good acoustical environment. Noises heard indoors are a major aspect of the overall noise problem.

Although noise can be a serious problem in almost any type of building, the present report is focused primarily upon dwellings. Noise heard in a dwelling can originate from within that dwelling, from within a neighboring dwelling, or from outdoors. Provision of an acceptable acoustical environment within a dwelling can be accomplished through quieting of noise sources, through provision of noise isolation from those sources, or through a combination of these two approaches. Thus attention could be directed to any or all of the noise control options shown in the following table:

Quieting of Sources	Provision of Noise Isolation
Within one's dwelling	Within a dwelling
Within a neighboring dwelling	Between dwellings
Outdoors	Outdoor-to-indoor

Current regulatory activities are focused primarily on quieting of outdoor sources. Quieting of indoor sources has been mainly sporadic and only in response to marketplace economics. However, regulatory actions, e.g., mandatory labeling requirements for household products, are now being considered by the U.S. Environmental Protection Agency.

In recent years there has been an increase in the number of building codes, within the U.S., that specify noise isolation between dwellings. However, the U.S. is still far behind most European countries in this area of regulation.

There have been essentially no regulatory actions concerning the provision of noise isolation within dwellings.

Recently, the California Administrative Code incorporated provisions that effectively specify, for new multifamily dwellings, outdoor-to-indoor noise isolation in areas having high outdoor noise levels. Other than this single case, there appear to have been no regulatory requirements on outdoor-to-indoor noise isolation in the U.S.

The noise environment within a dwelling results from sounds propagating along various paths from various sources. If criteria are established as to what constitutes an acceptable interior noise environment, it is rather straightforward to then derive either criteria for isolation from a given noise source or criteria for quieting a source so as to be compatible with a given noise isolation. In the present report, attention is confined to considerations of criteria for rating the interior noise environment and criteria for rating noise isolation.

Various procedures for rating human response to environmental noise, and their applicability to building codes, are reviewed in Section 2. Prior work on rating noise isolation is reviewed in Section 3. The interactions between noise isolation rating procedures and interior noise rating procedures are explored further in Section 4. The need to consider the temporal variation of noise, when specifying noise isolation, is briefly examined in Section 5. Section 6 includes a brief look at the relationship between outdoor and indoor noise levels for dwellings that are not near major outdoor noise sources.

2. ASSESSMENT OF ENVIRONMENTAL NOISE: APPLICABILITY OF VARIOUS RATING SCHEMES TO BUILDING REGULATIONS

People respond to their acoustical environment as a whole and not to the noise isolation of a particular structure or to the characteristics of a particular intruding noise. Thus, noise researchers must find a practical rating scale for assessing the entire interior acoustical environment from the standpoint of building users. If agreement can be reached on a scale, the degree of noise isolation needed to achieve a desired environment may be inferred.

People's reactions to noise depends upon the physical nature of the noise as well as social and economic factors. Even in a given socio-economic situation, different individuals may react differently to the same noise. For this reason, ratings of noise are needed which can predict with a reasonable degree of certainty the average response of groups of people.

2.1 Rating Schemes Based Upon One Aspect of Human Response

Human responses to noise are dependent upon three primary parameters of the noise: its sound level, its frequency spectrum, and the variations of both of these quantities with time. For a practical description of the noise, these three parameters are combined into a "single number" rating on a psychophysical scale which relates these noise parameters to the subjective response.

The selection of a particular psychophysical scale depends upon which aspects of human response are considered important for a given problem (e.g., loudness, noisiness, interference with speech communication, or interference with sleep). Presently, this selection is based upon judgment, owing to an incomplete understanding of the basic parameters affecting human response. Thus, numerous scales exist, reflecting idiosyncrasies of researchers and the diversion of goals responsible for development of a particular scale.

The "dose-response" relationship between the various noise environments encountered in buildings and the responses of building occupants must also be quantitatively established. A scale describing this dose-response relationship could be used to establish a criterion for noises that are judged undesirable or unacceptable.

2.1.1 Loudness

Much research conducted within the last 50 years has focused upon combining the frequency content and overall sound level of the noise into a metric related to the perceived magnitude (e.g., loudness) of the noise.

Although investigators disagree as to the details of the function relating the loudness experienced and the sound level of the noise, there appears to be a general consensus regarding the form of the function. Loudness is generally thought to grow as a power function of sound pressure level [1-3][1/]. In practical terms, each time a sound level is increased by 10 dB, the loudness experienced increases by approximately a factor of two.

Furthermore, the human ear is not equally sensitive to sounds of different frequencies. The relative sensitivity of the ear at various frequencies has usually been studied by determining the sound pressure level required for a given sound to give rise to the same loudness sensation as that produced by a reference sound at a prescribed sound level. Data from these studies are typically shown as a series of equal-loudness contours which indicate the intensities at which sounds of different frequencies produce similar loudness experiences.

Equal loudness contours have been determined in the laboratory under well-controlled conditions for pure tones [4-8] and for bands of noise [9]. Traditionally, contours have been developed with a reference sound which has been either a 1000 Hz tone or a noise band centered at 1000 Hz.

Results of studies of the kind described show that a person is most sensitive to sounds at frequencies between approximately 500 and 6000 Hz. That is, for a very broad-band noise the middle region of the audible frequency range contributes most to the sensation of loudness. However, results also demonstrate that as the sound pressure level of a sound increases from moderate to high levels, the relative contributions of low and high frequencies to the loudness perception increase until they equal that of mid-frequencies at very intense sound levels.

In order to compensate for the differential frequency sensitivity of human hearing, sound level meters are designed to weight the overall spectrum of the noise in such a way as to approximate the measured loudness-versus-frequency response of the ear. That is, when a sound is passed through the various networks of the sound level meter, each frequency region in the noise contributes to the total reading by an amount approximately corresponding to the subjective weighting of that frequency.

To take into account the findings that the frequency response of hearing varies with the overall sound level of the noise, three electronic networks are included in most meters. The A, B, and C networks were originally intended to represent the response of the ear to low, moderate and high intensities, respectively. However, over the years it has become apparent that the A-weighted sound level is a relatively good predictor of human response to broad-spectrum environmental noise [10-11] at all levels. For this reason, the A-weighted level is emerging now as the most widely used network when measurements are made with a sound level meter.

[1/] Numbers in brackets refer to the literature references at the end of this report.

The A-weighted sound level is only an approximate predictor of human response. For this reason, various investigators have attempted to improve the accuracy of prediction by using more detailed computation schemes. These schemes have become increasingly complex as more parameters relating to human response became known from further investigations.

Generally, refined schemes are based on a segmentation of the sound pressure spectrum of a noise into a series of contiguous frequency bands by means of electrical networks to analyze the distribution of sound energy over the audible frequency range. From data thus obtained, "loudness level" can be estimated by first assigning to each frequency band a loudness index designed to represent the potential contribution to the perceived loudness of the band. This index is then corrected by applying a weighting factor to account for the fact that bands with higher loudness indices may inhibit (or mask) the contributions of other bands. The weighted loudness indices are summed to estimate the overall loudness of the noise. A number of variants to this general approach are now available [12-21].

All of these procedures are complex. It is doubtful, therefore, that they would be practical for incorporation into building codes. Moreover, in most investigations comparing the A-weighted sound level performance to the more complicated schemes, it is found that the A-weighted sound level performs essentially as well as the more complicated methods in rating the noise environment with respect to human reactions [10-11, 22-24].

2.1.2 Noisiness

Kryter [25-29] has indicated that in many noise control problems it is not how loud a sound is that concerns us most, but rather how noisy and unwanted it is. Inherent in this statement is the assumption that loudness and noisiness are two distinguishable, although related, attributes of the human response to noise.

Kryter's findings were chiefly the outcome of a series of laboratory investigations of subjective response to aircraft noises. In these studies, ratings based on jury judgments of propeller and jet aircraft noises were compared to ratings based upon computed loudness levels. These comparisons indicated that the computed loudness consistently underestimated the noisiness or unwantedness of jet aircraft noise.

In another series of investigations by Kryter, loudness contours and noisiness contours for bands of noise and for pure tones were established, and then compared. These contours were determined by requiring subjects to equate (in terms of both loudness and noisiness) bands of noise and pure tones to a standard stimulus (typically an octave band of noise centered at 1000 Hz). The results of these studies indicated that subjects gave different responses depending upon whether they were matching the experimental stimuli for equal loudness or equal annoyance.

For example, at some frequencies perceived noisiness contours were as much as 5 to 10 dB lower than corresponding loudness contours. Kryter concluded that these findings were indicative of the fact that annoyance and loudness are indeed two distinct attributes of human response. Stevens [14] maintained that there was no conclusive evidence of a significant difference between loudness and noisiness as far as frequency weighting is concerned.

Kryter's findings led to the development of a new scale for assessing noise called Perceived Noise Level (PNL). This method is basically modeled after Steven's methodology [16] for calculating loudness. Thus, as in the computational procedures for loudness, the band levels are measured, then weighted indices are applied, and results summed up to arrive at a single number index. However, instead of assigning loudness indices to each measured band level, a perceived noisiness index is assigned. The unit of perceived noisiness is the noy and values are obtained from contours of equal perceived "noisiness".

Since it was originally proposed, the PNL methodology has been further altered to account for discrete frequency components of tones associated with aircraft noises as well as for the fact that, everything else being equal, aircraft flyovers of long duration are more annoying than flyovers of short duration [27, 29]. These developments are embodied in a rating procedure known as the Effective Perceived Noise Level (EPNL) [26].

In the computations of noisiness, the same assumptions and mathematical derivations were utilized as in the scales based on loudness. The only exception, as noted above, is that the loudness concept is replaced by that of annoyance. Furthermore, as in the development of methods based on loudness, those based on annoyance were chiefly derived from laboratory investigations with relatively few types of sounds.

Very recently, the "D-weighting network" has been standardized [30] for use in sound level meter measurements of aircraft noise. The D-weighting network has a frequency response that approximates the shape of the inverted 40 noy contour (which corresponds to a Perceived Noise Level of approximately 93 dB). Sound level meters do not sum contributions from different frequency regions in the same manner as is called for in the procedure for computation of the Perceived Noise Level. However, readings from a sound level meter using a D-weighting network generally agree (within a known additive correction) reasonably well with calculated Perceived Noise Levels, at least for sounds that lie in the range of, say, 80 to 100 dB SPL. Because of the high levels for which the D-weighting is intended, and because at present its use is normally restricted to outdoor aircraft noise measurements, it will not be considered further in this report as a candidate for use in building noise criteria.

2.1.3 Speech Interference

One of the most widely recognized effects of noise is the interference with auditory communication. Speech interference is one of the most annoying consequences of noise; thus there has been considerable interest in developing procedures to rate the acoustical environment in terms of its potential for interfering with speech.

The determination of criteria based on speech communication may include consideration of three factors:

(1) the vocal sound level, as a function of frequency and time, exerted by various speakers under various conditions;
(2) the degree of speech recognition in the presence of various types of noise; and
(3) the definition of acceptable speech communication for both speaker and listener.

Speech can be analyzed into a finite number of sounds which differ from one another in terms of their total sound level, duration of build-up and decay, and the distribution of sound level with respect to frequency. For example, the vowels as a group carry relatively large amounts of energy, distributed into harmonics of the fundamental frequency of the voice. These harmonics have distinguishable frequency regions which differ for each vowel. The consonants, on the other hand, carry much less energy, but the little energy that they do carry is found in higher frequency regions and over shorter durations than for the vowels.

The frequency range of speech extends from 100 to 6000 Hz. However, most of the information contained in speech is carried by the consonants, which, because they carry little energy, are easily masked.

As one speaks, the various basic sounds are combined into orderly sequences of phonemes to form syllables, which themselves are arranged into words and sentences. The result is an acoustical signal which undergoes rapid fluctuations with respect to sound level and frequency. In order for a listener to understand speech he must be able not only to detect the various sounds, but also to integrate and recognize the constantly shifting patterns.

When noise is present, some of the sounds and their shifting patterns are lost, and the speech becomes more difficult to interpret. As a result, speech intelligibility deteriorates in proportion to the sound level and bandwidth of the noise relative to those of the speech signal.

Observations such as the above were the basis for the Articulation Index, developed by French and Steinberg [31] as a means of estimating speech intelligibility from a knowledge of speech and noise spectra. This index represents a measure of the portion of speech which is available to the listener when communication occurs in a noisy system. In effect the

Articulation Index takes into account the sound level differential (i.e., signal-to-noise ratio) between speech and noise in 20 contiguous bands extending from 200 to 6000 Hz which, under optimal conditions, would contribute equal amounts to the Articulation Index.

The assumptions underlying the Articulation Index can be summarized as follows:

- the total variation in intensity levels of successive speech sounds is constant throughout each frequency region and roughly equal to 30 dB;
- the relative occurrences of intervals of different intensities are roughly identical for each frequency region;
- average (1/8-second) peak levels of single speech phonemes exceed the long-term average of the speech levels by about 12 dB for 10 percent of the time.

The Articulation Index, as originally proposed, requires frequency analysis in bands that are not readily measurable by available instrumentation. The standardized version [32] of the Articulation Index includes alternate procedures based on one-third octave or octave-band spectra.

The Articulation Index is based upon, and has been principally validated against, intelligibility tests involving adult male talkers and trained listeners [33]. Thus, the method cannot be assumed to apply to situations involving female talkers or children. Moreover, it estimates speech intelligibility in the presence of steady-state noise and contains provisions for predicting the effect of noise having a definite duty cycle. It does not purport to estimate the intelligibility of speech in the presence of fluctuating noise levels. Therefore, the Articulation Index must be used with caution in estimating speech interference in ordinary home and work situations. Finally, the complexity of the calculation procedure required to obtain the Articulation Index limits its usefulness for the measurement and monitoring of noise levels on a routine basis.

The Speech Interference Level (SIL), which is being proposed as an American National Standard, is a simple numerical method for estimating the speech-interfering aspects of noise based on physical measurements of the noise. Unlike the Articulation Index, SIL does not include specific consideration of the level and spectrum of the speech. Rather it employs a table or a nomograph for estimating, in terms of general voice level and distance between communicators, the noise levels which will seriously restrict speech communication.

Originally, the Speech Interference Level, SIL, was defined [34] as the arithmetic average of the sound pressure levels in the three octave bands: 600 to 1200, 1200 to 2400, and 2400 to 4800 Hz. In terms of the new, or preferred, band-center frequencies [35] several definitions have been considered, two of which are worthy of note: (1) the "preferred-frequency speech interference level", PSIL, which is the mean level of the octave band levels centered on 500, 1000, and 2000 Hz, and (2) the speech interference level, SIL(0.5-4), defined as the mean level of the octave band levels centered on 500, 1000, 2000 and 4000 Hz. This latter is the version being considered for adoption as an American National Standard.

For steady-state noises, either version of the Speech Interference Level is a reasonable predictor of the relative ranking of noises with respect to their speech-interfering properties. That is, two noises which are equally-interfering with speech communication will have very similar Speech Interference Level ratings (typically within 5 dB). Speech Interference Level can be used for rough, quantitative estimation of monosyllabic word intelligibility in the presence of continuous, random noise. However this procedure is not appropriate for noise spectra with considerably more energy at high frequencies than at low frequency, or when any of the following conditions exist: (1) the level of the noise is not of a continuous-in-time, steady-state nature; (2) the frequency spectrum of the noise is not constant with time; and (3) the speech and noise are subject to perceptible echo or reverberation.

Webster and Klumpp [24] have developed charts which can be used to estimate the voice level and maximum allowable distance between talker and listener for satisfactory face-to-face communication as limited by ambient noise levels having various values of Speech Interference Level. For many types of noise, the Speech Interference Level can be approximated by the A-weighted sound level [10]. Because the A-weighted sound level can be read directly from a sound level meter, it is an easier measure to obtain than SIL.

While both the Articulation Index and the Speech Interference Level can be extremely useful, there is a need to develop predictive techniques for speech interference with male and female speakers, both adult and child, and untrained listeners in real situations, rather than in the laboratory. Consideration should also be given to the additional problems for listeners suffering from impaired hearing. Statistical predictors that take into consideration the speech-interference aspects of fluctuating noises, such as those produced by traffic, are also needed.

The data base regarding speech levels embodied in the speech interference schemes comes from a very limited set of measurements. The total number of talkers on which present criteria are based is surprisingly small (total 35 subjects). In addition, most of the data relate to male speakers and none are available on children's speech.

Crandall and McKenzie [36] used 5 male speakers; Dunn and White [37] studied the speech of 6 males and 5 females; Rudmose, Clark, Carlson, Eisenstein and Walker [38] used 7 males; Stevens, Egan and Miller [39] studied speech from 1 male and 1 female speaker; Benson and Hirsh [40] used 5 males and 5 females; and Pickett and Pollack [41] used 5 males. Other speech data found in the literature are traceable to the works already mentioned.

One of the most consistent findings among the studies noted above is the great variability among speakers. For example, Dunn and White report sound power level differences among speakers of the same sex of the order of 18 dB in some frequency regions, while Rudmose *et al.* report differences of the order of 10 dB. However, as observed by Galloway [42], when the data contained in the various papers are analyzed in terms of band levels relative to overall levels, the variability of any given band is reduced to about 4-5 dB. Thus, one may conclude that while speakers vary as to their power output, the various band levels relative to the overall level are fairly stable from one study to the next. However, the total speech power output is an important determinant of the amount of sound energy available to the listener for interpretation.

There are some discrepancies among the data of various researchers in terms of both the level of speech and the form of the spectrum during "normal conversational speech." For example, Dunn and White report a concentration of energy in the 500 Hz region in male speech; this does not appear in the Benson and Hirsh data and is somewhat ambiguous in the Rudmose *et al.* data.

In addition, Dunn and White report 66 dB (re 20 µPa) as the normal conversational level of speech at one meter for male subjects. This figure agrees well with the data of Rudmose *et al.*, in which a value of 68 dB is reported (when computed from their reported sound power level) but disagrees with the value of 57 dB reported by Benson and Hirsh.

The reported overall long-term, root-mean-square sound pressure level of normal male speech has varied among studies and among individual speakers within a given study, as indicated by the results shown in Table 1.

Table 1. Long-Term, Root-Mean-Square Speech Levels of Male Speakers, Corrected to a Distance of One Meter in Front of the Lips

Investigators	Sound pressure level, re 20 µPa, dB		
	Mean of Subjects	Max Subject	Min subject
Dunn and White [37]	66	70	60
Rudmose *et al.* [38]	68	72	60
Benson and Hirsh [40]	57	57	56

Since the total number of subjects on which the data are based is very small, and the variations among subjects are very large, it is impossible to assess the significance of the differences found among the various studies, both with respect to actual value and to spectral shape.

In addition, some inconsistencies appear to be present in the speech spectra given in the American standard for computing the Articulation Index [32]. Specifically, if one uses the spectrum level (i.e., the level corresponding to a 1-Hz bandwidth) given in that standard for use in conjunction with the "20-band method" to compute the equivalent 1/3-octave band spectrum, differences ranging from 2-5 dB between the 20-band and the third-octave spectra exist at frequencies above 1000 Hz as shown in Figure 1. Since both spectra are derived from the same data, and since both are purported to represent voice level during normal conversational speech, there should not be any difference between the two spectra.

An additional problem is associated with the speech data upon which all speech criteria rest. As observed by Galloway [42], in the development of the Articulation Index and other methodologies, only the data of Dunn and White were available to define the statistical distribution of speech level. Furthermore, since the Dunn and White data appeared to suggest that the statistical distribution of speech levels was similar in all bands for both male and female speakers, only the data of the 1000 to 1400 Hz band obtained on male subjects were used in the development of the Articulation Index. Thus, present speech criteria are traceable to only one study of the statistical distribution of speech levels done 35 years ago and rests upon the data obtained on only 6 male subjects in a frequency range between 1000 and 1400 Hz!

Although Kryter [33] provides comparisons of predicted and measured intelligibility of speech in the presence of widely different noise spectrum shapes and various signal-to-noise ratios, his data validate the Articulation Index method only for continuous spectra and for male speakers. Since it is reasonable to assume that in most households women and children do talk (some would even say too much) it is unlikely that one could justify a design goal for dwellings on the basis of data that excludes all such persons.

2.2 Rating Schemes Based Upon Several Aspects of Human Response

2.2.1 Combined Speech Interference and Loudness

In an effort to "bridge the gap" between schemes developed chiefly from laboratory investigations and the real life situations associated with the experience gained by the consultant working in the field, Beranek [43] proposed the Noise Criteria Curves (NC) which embody considerations of both loudness and interference of noise with speech communication. The Noise Criteria curves represent, as far as is known to the present writers, the first attempt to arrive at criteria based upon both laboratory data and consulting experience gained in the field.

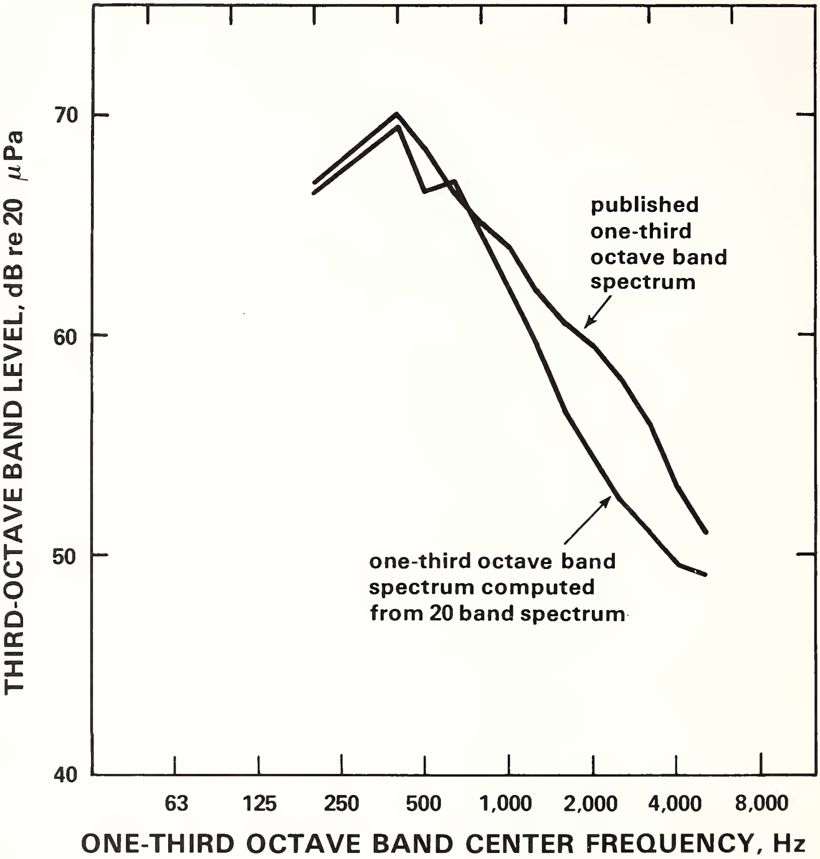

Figure 1. One-third octave band spectrum, as published, compared with that computed from spectrum level, as published, in the current American National Standard for the calculation of the Articulation Index [32].

The Noise Criterion Curves (NC), introduced in 1957, specify the maximum noise levels that can be present in each octave band of noise to meet a specific NC criterion. These criterion curves were in turn derived from another set of curves, the Speech Communication Curves (SC) [44-45]. The Noise Criteria Curves and Speech Communication Curves are reproduced in Figures 2 and 3, respectively.

The SC curves are generally similar in contour to the NC curves, but are approximately parallel to one another at a separation of about 10 dB in most of the frequency range. At low frequencies the SC curves have steeper slopes than do the NC curves. Although Beranek [45] did attempt to describe the actual process by which the SC curves were modified to become the NC curves, the process is not clear, as pointed out by Schultz [46]. It can only be conjectured that the reason for the change was that the NC curves conformed better to the loudness contours, and, therefore, may have been thought to be in closer correspondence to the hearing mechanism.

The data on which the SC and NC curves were based included an extensive research study of attitudes and opinions of office workers regarding noise and its effects on their ability to perform work and to communicate by speech. The opinions were obtained through the use of rating scales. These were then correlated with various physical measures of the noises present in the offices studied. The respondents in these studies were chosen among office workers at a large Air Force Base and among office workers in several commercial office buildings where noise problems existed and were corrected in response to occupant complaints [45,47].

The office studies revealed that occupants were conscious of the ambient noise levels and their effects on speech communication. It was also found that low frequency sounds were annoying even when they were not sufficiently intense to mask speech sounds. The two important parameters that emerged as particularly useful in assessing the way in which people rate acoustic spaces in office buildings were the Speech Interference Level (SIL) and the Loudness Level (LL). Furthermore, results indicated that acceptable conditions were achieved when the SIL values did not exceed 40 dB and the noise spectrum was maintained within a shape that yielded a LL that was 22 units above the values of the SIL. The SC curves were derived using these findings.

In subsequent work, the NC curves were presented together with a table delineating the NC values compatible with conducting various activities in buildings such as churches, hospitals, and homes [47]. The precise computational procedure by which these values were derived are unclear. The NC curves do, however, correspond closely to other criteria presented by Knudsen and Harris in terms of A-weighted sound levels [48].

The NC curves have received widespread acceptance both in the United States and in Europe. They are often used in stating design goals for

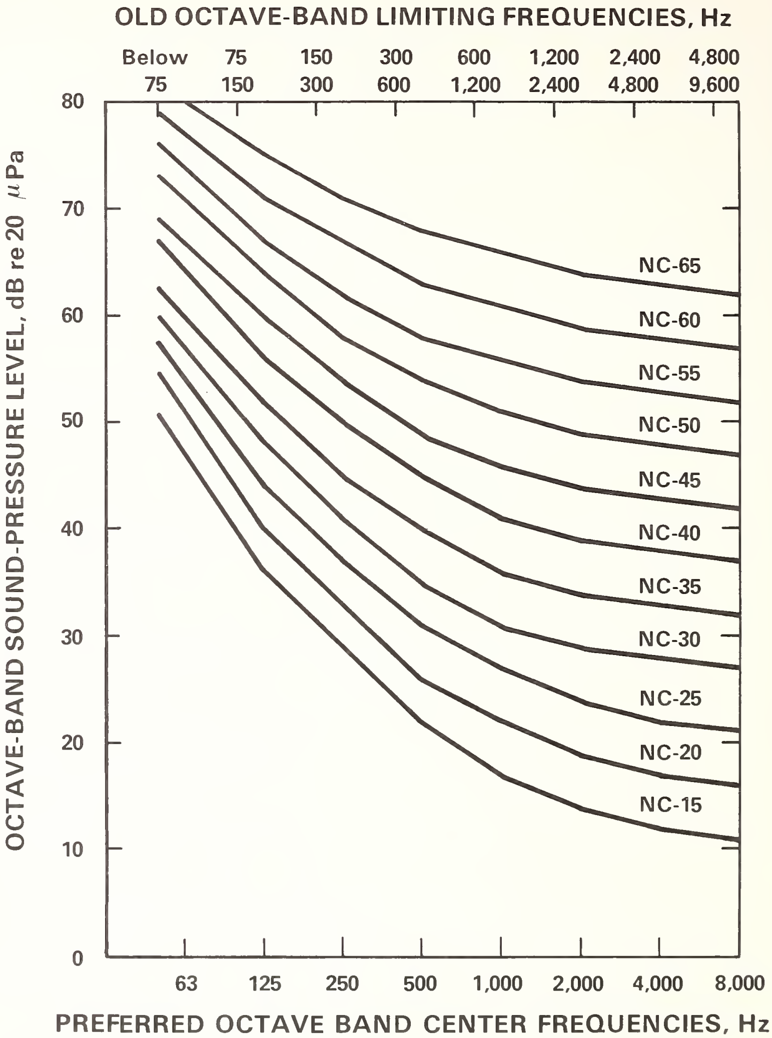

Figure 2. Noise Criteria curves [52].

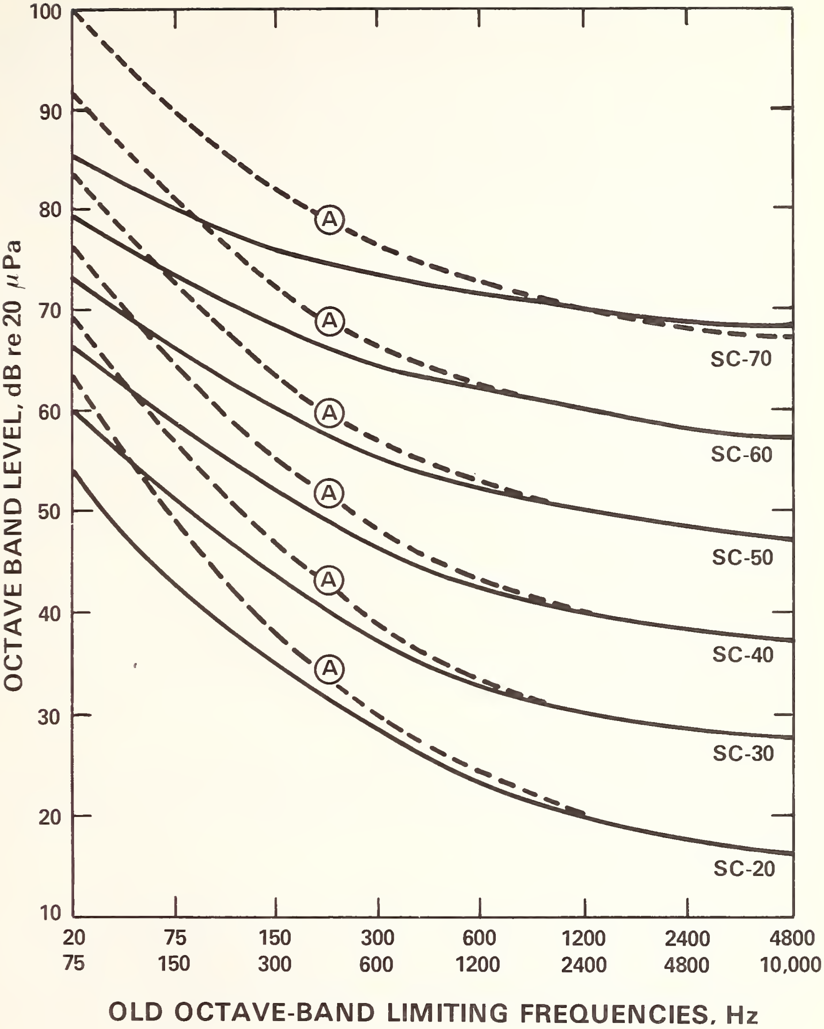

Figure 3. Speech Communication curves [46].

buildings. Rather similar curves, the Noise Rating Curves (NR) have been standardized internationally [50].

Recently it has been demonstrated that if one deliberately generates a spectrum that conforms to the NC curve, the sound heard does not appear natural. It is unpleasant because it is perceived as being both "hissy" and "rumbly" [50]. These observations suggest that the effect of the low frequencies and high frequencies upon human response are underestimated by the NC curves. As a result of these findings, a new set of curves, the Preferred Noise Criterion (PNC) curves have been proposed as a replacement for the NC curves [50-51]. This new set of curves, shown in Figure 4, calls for lower spectrum levels at both high and low frequencies than do the original NC curves.

The early studies of Beranek were conducted because of auditory environments which had produced complaints. The purpose of developing the noise criterion contours was merely to lower the rate of complaints to "tolerable" levels. This goal is quite different from a design goal based upon optimal conditions.

Moreover, all of the data upon which the NC methodology was based came from investigations of office noises. Although the methodology has been extended to other types of buildings, including dwellings, no evidence has been set forth indicating that requirements for quiet in the home are identical to those for offices. Consequently, unanswered questions remain regarding the validity of extending this particular approach to the problem of noise in dwellings.

Another important drawback to the NC methodology is that the available data are based upon continuous noise spectra. They do not account for the time variation of noises, which may prove to be one of the most important parameters in the subjective assessment of interior spaces.

2.2.2 Community Response

Since the early 1950's, a number of investigations conducted in several countries have combined social surveys and physical noise measurements to assess the effects of environmental noise in residential areas.

Although these studies had a similar goal -- to arrive at a methodology for relating the human response to environmental noise to the physical attributes of that noise -- a variety of methods has evolved to interpret the data. These include, for example, the Community Noise Rating (CNR), the Noise Exposure Forecast (NEF), the Community Noise Equivalent Level (CNEL), the Noise and Number Index (NNI), and the Traffic Noise Index (TNI).

A priori, it may appear that these ratings are widely different; yet, they share many attributes. The similarity among ratings is reflected by the fact that they are all highly correlated, with a correlation coefficient of the order of 0.9 [52]. (This high correlation occurs, in large part, because all of the ratings rise at essentially the same rate with increases in sound pressure level.)

Basically, there are two ways of assessing community response to environmental noise exposure. The first is to examine the action, such as complaints to officials or law suits, taken by individuals, or groups of individuals, against identifiable noise sources. The second approach is to examine the responses made by people interviewed in social surveys.

The responses of people to questionnaires administered in social surveys in the United Kingdom [53-56], Sweden [57-60], Austria [61-62], France [63-66], the Netherlands [67] and the United States [68] reveal that people exposed to environmental noise in residential areas show an adverse reaction to noise. The adverse general reaction of people to environmental noise is complex and involves a combination of factors. These include: interference with speech communication, interference with sleep, a desire for a tranquil environment, and the ability to use telephones, radios, and televisions satisfactorily. The results of all studies indicate that in the aggregate the *average* response of groups of people is predictable and highly correlated with a number of different measures of cumulative noise exposure. However, while the average response of people is predictable, individual responses vary greatly.

Social survey data are in agreement with the general overt responses of people to noise. Citizens' actions against noise have taken many forms, ranging from the registration of a complaint to court actions. Although the rate of complaints has been found to be only a partial indicator of the number of people annoyed in a community, predictable relationships exist among rate of reported annoyance, rate of complaints, and environmental noise levels [69].

As noted above, the surveys have led to a number of different procedures for rating environmental noise. It is not the intent of this section to review all of these rating schemes. However, the evolution of one of the families of community noise assessment procedures is given to illustrate the common elements among rating schemes which appear to be widely different.

In the United States, the first method proposed for assessing community reaction to noise was that of Bolt, Rosenblith and Stevens [70], known as the Composite Noise Rating (CNR). Originally it was proposed merely as a scheme for interpreting community reaction to noise exposure in eleven case studies of different noise sources. Thus it was derived from insights gained from consulting practice and from interpretations of the limited research data then available.

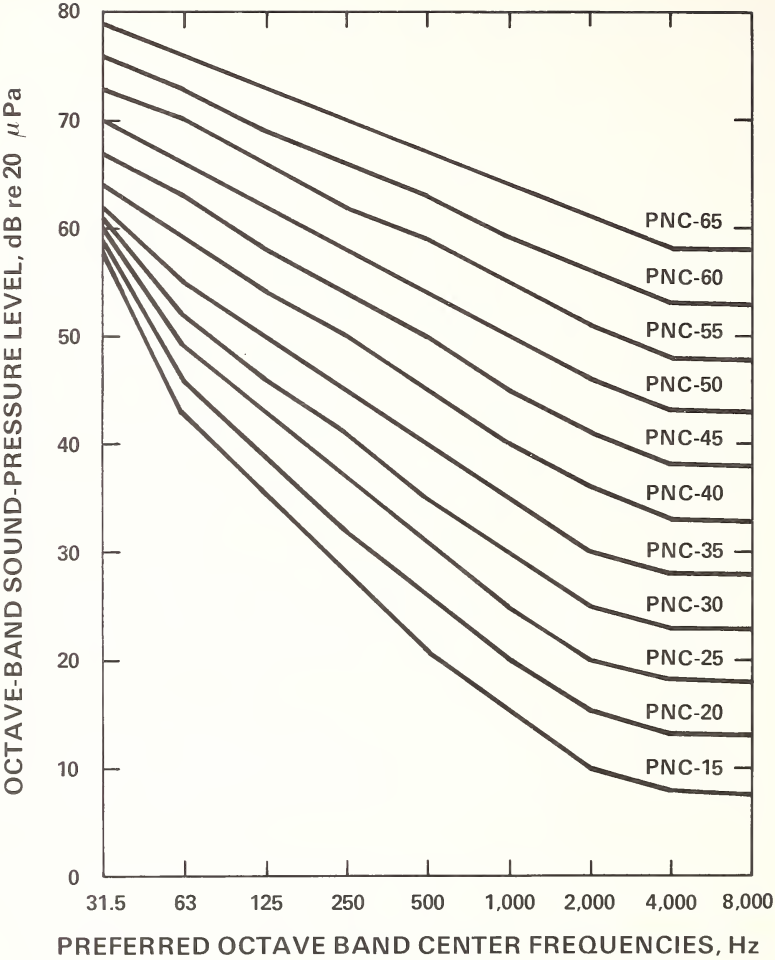

Figure 4. Preferred Noise Criteria curves [51].

The original Composite Noise Rating specified that the noise was to be measured and plotted as octave-band sound pressure levels. The resulting graph would then be compared to a family of curves, which somewhat resembled loudness contours, plotted for 5 dB intervals in the region of the mid-frequencies. On the basis of these comparisons, a noise rank level was assigned to the noise, corresponding to the highest rating curve into which a measured spectrum intruded. The value thus obtained was then adjusted by a series of noise corrections based on: noise spectra, ambient community levels, "intrusiveness", "impulsiveness", "repetitiveness", and previous exposure of the community. Further corrections were applied to account for the time of day and the period of year during which the noise intruded.

Each correction factor had the effect of either raising or lowering the rank level originally obtained. A range of discrete community responses, as a function of CNR, was also provided for the purpose of estimating the probable effect of a given noise. These responses were: "no reaction", "sporadic complaints", "widespread complaints", "threat of legal action", and "vigorous community reaction".

Since its proposal in 1955, the method has undergone numerous changes. One was the substitution of the Perceived Noise Level as a means of determining the noise level rank. Additional refinements were added to the correction system as more data became available. Finally, a scheme for computing the effects of a large number of separate events was incorporated into the system. Eventually the method was modified into what is now the Noise Exposure Forecast [71], which is part of the procedure utilized by the Federal Aviation Administration for assessing land use around airports [72].

3. SPECIFICATION OF NOISE ISOLATION IN BUILDINGS: EVALUATION OF TECHNICAL BASES UNDERLYING CURRENT PRACTICES

Scientific attention to noise isolation between dwelling units dates back to Sabine's work near the turn of the twentieth century. By the late 1930's, national building codes, primarily in Europe, began to incorporate requirements for the sound insulation of dwellings. In these codes, the approach has usually been to specify the acoustical performance which various interior building elements, such as floor-ceiling assemblies and party walls, must achieve in order to be acceptable. Social survey data, on the other hand, indicate that the responses of people to indoor noise levels are somewhat dependent upon the acoustical climate outdoors. For example, everything else being equal, people who live in noisy areas seem to be less aware of their neighbors' noises than are people who live in quiet areas. Yet, none of the national building codes have specified requirements for outdoor-to-indoor isolation.

In the present section, attention is given to the development of criteria for noise isolation and the evidence, or lack thereof, in support of those criteria.

3.1. "Isolation" versus "Insulation"

The large majority of building codes have specified the sound transmission loss, or insulation, to be provided by a particular building element, such as a wall or a floor-ceiling assembly. However, there is a serious problem with an approach based upon specifying the sound transmission loss of separate building elements in that reliance is placed on an isolated structural element regardless of how it may be built or installed and irrespective of the existence of flanking sound transmission paths. Indeed it is not unusual that a particular set of building elements may have received an excellent laboratory rating, but be assembled into a finished product that is poor [73-75]. Consequently, in recent years there has been an increased recognition [76] of the need to shift the emphasis in building codes from the sound transmission loss of individual building elements to the noise isolation, or level difference, between spaces. Specifications of sound transmission loss should provide assistance to the building designer in achieving the desired performance, but the criterion should be the isolation required, rather than the sound transmission rating, since a specified performance for individual structural components may or may not lead to the desired isolation.

In some of the literature reviewed, the distinction between the concepts of isolation, or level difference between rooms, and insulation, or sound transmission loss of a building element, has not been clearly made, thus resulting in some confusion in comparing the results of different investigators.

3.2. The Grading Curve for Indoor-to-Indoor Isolation

3.2.1. Origin

Typically, the transmission loss of a partition at each frequency is measured according to well-defined and prescribed rules [77-78]. The results of these measurements are then expressed in a graphic form by plotting the transmission loss as a function of frequency, typically over a range of 16 to 18 one-third octave bands ranging from approximately 125 to 4000 Hz. While detailed data may be useful in engineering design applications, in specifying performance criteria for building codes a single number rating of the overall performance of a partition is more practical, especially for enforcement purposes. Accordingly, various single-number rating schemes evolved and were adopted in various codes and standards.

For some years, requirements for sound insulation were usually stated in terms of the arithmetic mean of the transmission loss values (expressed in decibels) over the range between approximately 100 and 3000 Hz [79]. This scheme was soon found to be unsatisfactory. The averaging procedure allowed for two partitions with very different characteristics to achieve the same rating. One of them might have good transmission loss throughout the whole frequency range, while the other might have poor transmission loss in one region offset by superior transmission loss in another region. This feature of the rating scheme was recognized and a new approach was developed in the 1950's. The new approach is to state noise insulation requirements in terms of the performance relative to a standard reference curve (or grading curve) [80] .

If the transmission losses of a given partition are found to exceed those of the grading curve at all frequencies, the partition is clearly acceptable. If the transmission losses at all frequencies are found to be poorer than those specified in the grading curve, the partition is clearly unacceptable. Most partitions, however, are neither all "good" nor all "bad". Rather, in the typical situation the transmission loss may be better than that embodied in the grading curve at some frequencies while falling below the requirements at other frequencies. For this reason, rules had to be devised for making the comparisons between a measured transmission loss curve and the grading curve to limit unfavorable deviations to a "reasonable" amount.

In Germany, where the above scheme was first proposed [81] in 1953, the acoustical performance of a partition is expressed in terms of the number of decibels by which the grading curve must be either lowered or raised in order that the mean of the unfavorable deviations from the grading curve does not exceed 2 dB. The resulting number is accompanied by a positive or negative sign indicating whether the grading curve must be moved upward or downward. In England, the mean of the unfavorable deviations (below a different grading curve) is not allowed to exceed 1 dB [82]. In either case, only the deviations that fall below the grading curve are used in the computations of the mean of the unfavorable deviations.

Developments similar to those described for Germany and England have occurred in various countries. Although the details vary, the approaches have been similar enough to enable the International Organization for Standardization (ISO) to arrive at a recommended method for assessing the relative performance of partitions with respect to their ability to act as sound barriers [83].

In the United States a standard method for assessing partition performance has also been adopted [84]. This method, developed by the American Society for Testing and Materials (ASTM), is similar to the ISO standard. According to the ASTM procedure, the sound transmission loss of a partition is measured in conformance with a defined procedure at 16 one-third octave frequency bands centered at the frequencies from 125 to 4000 Hz. The results are then plotted as a function of frequency and compared to a reference curve which is adjusted vertically relative to the test curve until the following conditions are fulfilled:

- the sum of the deficiencies (that is, deviations below the reference contour) do not exceed 32 dB;

- the maximum deficiency at a single test point does not exceed 8 dB.

When both requirements are met, the Sound Transmission Class (STC) of partition is given by the transmission loss value "corresponding to the intersection of the reference contour and the 500 Hz ordinate."

Implicit in the American Sound Transmission Class, or the similar International procedure, are two critical assumptions:

(1) it is known what overall insulation against intrusive noises is adequate in terms of minimizing adverse human responses;

(2) it is known how deviations, from the desired performance, at various frequencies influence human response.

With these assumptions in mind, it is interesting to look at the experimental evidence behind current practices. A review of the origin of the grading curve used to judge partitions indicates that the data upon which it rests are not entirely satisfactory.

3.2.2. Evidence from Social Surveys

Historically, tenant complaints came about at a time when the building industry was departing from traditional masonry construction practices and moving toward the use of lightweight, prefabricated structures. In older constructions, where the rate of tenant complaints was low, dwelling units were often separated by a 25-cm plastered brick wall whose massiveness was intended primarily to serve as a fire wall. The smoothed transmission loss curve for this brick wall was taken as the criterion against which other structures should be judged. It was only after this decision was generally agreed upon that a number of investigations were carried out to provide the data to validate the choice of this transmission loss curve.

The chief approach taken by numerous investigators to acquire the necessary validation information was to conduct social surveys to identify those structures deemed acceptable by the majority of building occupants. Subsequently, sound transmission loss measurements were taken, either in the field or in the laboratory, on these structures. Such surveys were conducted in England [85-86], Sweden [87-88], Holland [89], and France [90].

a. The British Surveys

Two surveys [85-86] conducted in England involved both objective measurements of sound insulation and social surveys of tenant satisfaction. In the first survey ("Survey 2" in [85]), conducted in 1950, 500 pairs of semi-detached houses were studied. Half of the pairs of dwellings had 9-in. (23 cm) solid brick party walls while half had two-layer concrete walls separated by an air cavity. The cavity wall provided higher transmission loss at high frequencies than did the solid brick wall. Inhabitants of both types of houses were questioned about the general conditions in their dwellings and whether they felt that the walls were providing adequate sound insulation.

The results of this study indicated that the traditional 9-in. brick wall provided sufficient sound insulation, since tenants of dwellings separated by such walls did not complain particularly about noise. The increased sound insulation provided by the cavity wall at high frequencies did not lead to a perceptible decrease in complaints. Finally, it was determined that people judged their indoor noise environment in a manner related to their outdoor noise environment. People who lived in "noisy" areas tended to be less disturbed, and more often unaware, of their neighbors' noises than people who lived in "quiet" areas.

In 1952/1953 a survey ([86], "Survey 3" in [85]) was made to assess the subjective response of people living in apartment buildings. In this survey three groups of apartments were studied. The average transmission losses (averaged over 100 to 3150 Hz) of the walls were similar for all apartments and were comparable to that of the traditional brick wall. However, the party floor-ceiling assemblies had average airborne sound insulation values of 49, 44, and 39 dB.

The results of this survey indicated that apartment dwellers in general were more annoyed by their neighbors' noises than were people in townhouses. In apartments having an average airborne sound transmission loss of 49 dB, 22 percent of the people were disturbed by noises made by their neighbors, but were not more disturbed by noise than by other conditions associated with living in apartments. In apartments with an average transmission loss of 44 dB the incidence of reported disturbance increased to 36 percent. Moreover, for these people, noise was found to be the single greatest factor leading to complaints.

Surprisingly enough, the rate of complaints among people living in apartments having an average transmission loss of only 39 dB was only 21 percent. Close scrutiny of the data, however, revealed that people who lived in the apartments with the poorest sound insulation were generally from a lower socio-economic class. Furthermore, this group of people had been waiting for a long time to move into their apartments, and had previously been living under much worse conditions. These people did not complain about any aspect of their dwellings even though they usually experienced some overcrowding due to the large sizes of their families.

The aforementioned British studies have sometimes been cited in support of the choice of the brick wall as a sound insulation criterion. In our opinion, however, the data gathered in these studies do not appear to provide the desired support for the following reasons:

(1) All of the people interviewed in the two British studies were relatively low on the socio-economic scale. Since these people were all living in subsidized housing, their standard of living and their expectations may have been different from those of other socio-economic groups.

(2) At the time that these studies were being conducted, England was only beginning to recover from the effects of World War II and still suffered a significant housing shortage. Under those conditions any degree of privacy in housing might have been acceptable.

(3) The samples of transmission loss studied covered a limited range of sound transmission loss. None of the wall structures provided significantly better insulation than did the classical brick wall.

(4) In the second study, the three groups of apartments differed only with respect to the sound insulation of the floor-ceiling assemblies. It is therefore unclear whether people responded to airborne noise or to impact noise.

b. The Swedish Surveys

While the British studies were underway, similar but independent efforts were carried out in Sweden [87-88]. The Swedish studies involved a set of 500 apartments divided into three groups on the basis of the sound transmission loss provided by the walls. A physical measurement program was combined with a social survey study.

The data generated in these studies were in good agreement with those obtained in the British studies. Generally, it was found that the rate of complaints decreased as the amount of sound insulation increased. When the average transmission loss was 45 dB, 21 percent of people complained about their neighbors' noises. The complaint rate dropped to 16 percent with an increase in the transmission loss to 50 dB, and to 7 percent with a further increase in the transmission loss to 55 dB. However, as in the British studies, other non-acoustical factors contributed to people's judgments of their acoustical environment.

It may appear surprising that the results of the British and Swedish studies agreed so closely, since the standard of living in Sweden at that time was considerably better than that of postwar England. However, Sweden had a chronic and severe housing shortage that might explain the similarities among the Swedish and the British findings.

c. The Dutch Survey

A study similar to those conducted in England and Sweden was also carried out in the early 1950's in Holland [89]. This study involved a set of 1200 apartments and 1200 survey respondents. Unlike the previous studies, the Dutch data failed to reveal a correlation between people's satisfaction and the sound transmission loss of party walls. The reasons for the discrepancy between the data obtained in the Dutch survey and those obtained in the British and Swedish surveys are not clear.

d. The French Survey

A study similar to those conducted in England, Sweden and Holland was more recently performed in France [90]. In the French study, six groups of dwellings were involved and 266 responded surveyed. The dwellings studied in this investigation were chosen on the basis of their conformity to the French Construction Standards, which are modeled after the smoothed transmission loss curve for the standard brick wall. The results of the French study reveal that, despite the fact that all the dwellings met the French norm, 40 percent of the people interviewed reported hearing their next door neighbor's television and radio. Similar results were not found regarding conversations. On the basis of the French data, it can be surmised that, while the traditional brick wall may have once provided adequate isolation for certain noise sources, it may provide insufficient protection against amplified music, television, and radio sounds (i.e., amplified conversation) as well as against modern appliances or household equipment.

e. Summary of Social Survey Evaluations

The results of the various social surveys, with the exception of that performed in Holland, seem to indicate that:

- tenant satisfaction with acoustical privacy is related to the degree of sound transmission loss provided by building elements;

- everything else being equal, the response of people to indoor noises is influenced by environmental noise conditions outdoors;

- while the selection of the acoustical performance of the traditional brick wall as a design goal for party walls may have been appropriate at one time, it is perhaps no longer adequate.

3.2.3. Evidence Based Upon Consideration of Loudness and Noisiness

Possibly because of the discrepancy between the Dutch survey data and the British and Swedish survey data, van den Eijk [91], in Holland, examined a different approach to the problem. His first assumption was that one could not be annoyed by a noise which one could not hear. Consequently, if one could specify the statistical distribution of sound levels for the most annoying noise source, a knowledge of loudness functions should enable derivation of the insulation required to produce a zero loudness level in a space adjacent to the noise source room.[2]

Radio sounds had been found in the British survey to be the predominant source of complaints among apartment dwellers. Van den Eijk determined the peak levels of radio programs in each of 8 octave bands having center frequencies from 50 to 6400 Hz. This distribution was derived from data obtained for a radio working continuously through 17 mornings and afternoons. The results were presented as a series of curves showing the peak levels exceeded in each frequency band during various percentages of time. These results are reproduced in Figure 5.

From the data contained in Figure 5 and from the Fletcher-Munson equal-loudness contours [4], another series of curves was generated. These curves were designed to specify the necessary sound transmission losses in each octave band that would yield a loudness level of 0 phon in an adjacent room for various percentages of the time. The resulting values can be seen in Figure 6.

Inspection of Figure 6 reveals that the shape of the curve derived on the basis of loudness is quite different from the German standard "Soll-Kurve" (based upon the standard brick wall). Specifically, the curve derived on the basis of loudness drops sharply below 400 Hz and

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[2] Actually, van den Eijk's procedure led to requirements for noise isolation, or level difference between rooms, and not to the sound transmission loss, or insulation, of the partition between them.

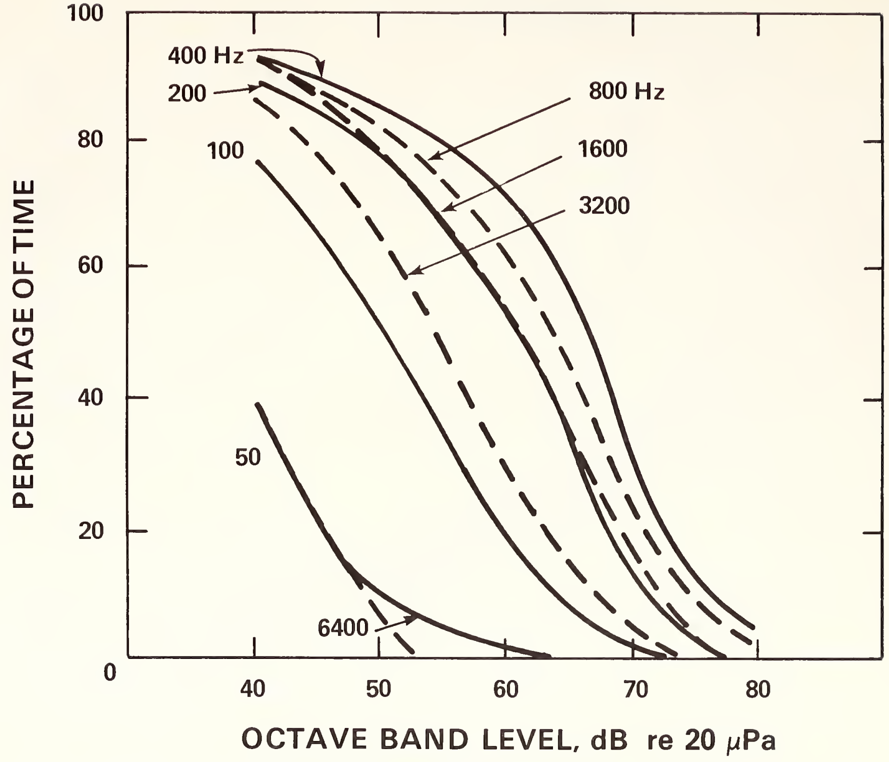

Figure 5. Percentage of time that a given peak level is exceeded in radio programs, for various octave bands [92].

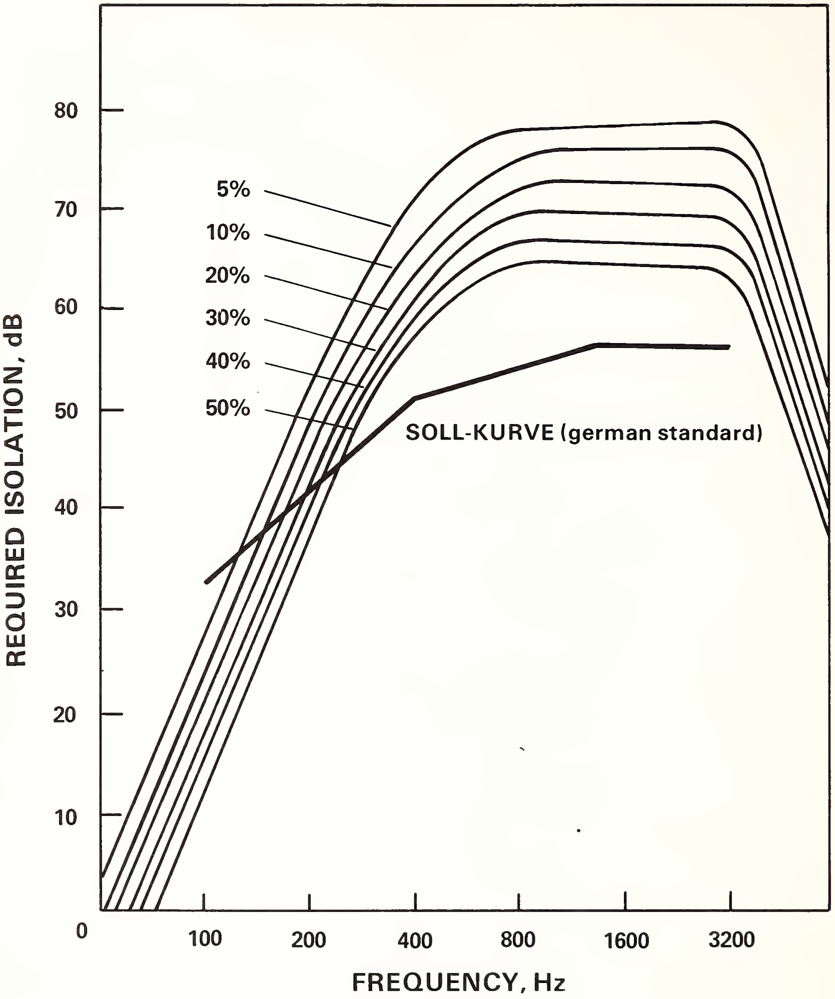

Figure 6. Required isolation, according to van den Eijk, in order that peak levels due to a neighbor's radio not exceed 0 phon for more than the specified percentage of the time [92].

above 3200 Hz whereas that derived from the brick wall does not. In the range between 400 Hz and 3200 Hz the curve based on loudness is essentially flat while the other is not. Furthermore, the requirements based upon a 0 phon loudness level are much stricter than those of either the German or British standards. To reduce radio noise to this extent, the sound isolation required could be prohibitively expensive.

Thus, van den Eijk also estimated the isolation required to reduce the levels he measured for radio programs to a loudness contour of 20 phons in the receiving room. The results of these computations are shown in Figure 7, together with the requirements embodied in the German standard (i.e., the Soll-Kurve). As can be seen in Figure 7, if a 20-phon loudness contour is used instead of a 0-phon loudness contour, van den Eijk's derived isolation requirement would more nearly be in agreement with the Soll-Kurve, insofar as average level is concerned. However, the differences concerning the shape of the curves remain.

Based upon the previous analysis, van den Eijk concluded that the most important frequency range for airborne sound insulation is from 400 to 800 Hz, since the insulation required is controlled by the contributions in this frequency region. He further hypothesized that if the noise is allowed to intrude next door at a low or moderate level (e.g., 20-phon loudness level), it should not be annoying. Van den Eijk reports that his transmission loss requirement curve is based upon an intrusion of radio programs for 10 percent of the time at a loudness level of 20 phon. Thus, the Dutch Building Code, which specifies the insulation required in each octave band between 250 Hz and 2000 Hz, was derived partially on the basis of allowing radio sounds to intrude next door by the above amount.

A number of questions are raised by the work of van den Eijk. He computed the isolation required in order that each octave band, taken alone, lie on the 20-phon contour. However, if there are a number of bands, each of which singly produces a loudness level of 20 phon, the overall estimated loudness level in the receiving room will exceed 20 phon by an amount which increases with the number of contributing bands. Specifically, if each octave band taken alone produces a loudness level of 20 phon, it may be reasonable to assume that each band contributes equally to the loudness level in the receiving room. Accordingly, the incremental loudness level in the receiving room as a function of the number of bands present can be estimated using various computational procedures. The results of these computations are shown in Figure 8 for the Fletcher-Munson [4], the Stevens' Mark VI [12,13], and the Stevens' Mark VII [14], loudness calculation procedures. As can be seen in Figure 8, the overall loudness level for the 8 bands utilized by van den Eijk might be about 16 to 18 dB above that of each individual band, depending upon

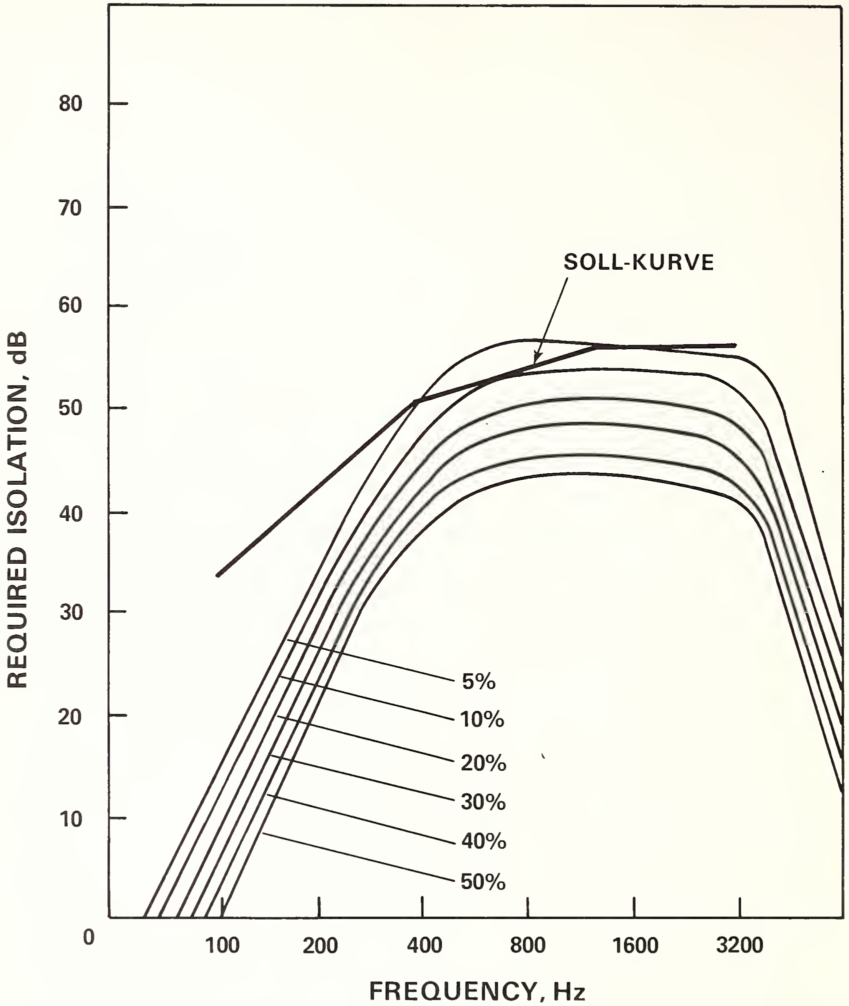

Figure 7. Required isolation, according to van den Eijk, in order that peak levels due to a neighbor's radio not exceed 20 phon for more than the specified percentage of the time [92].

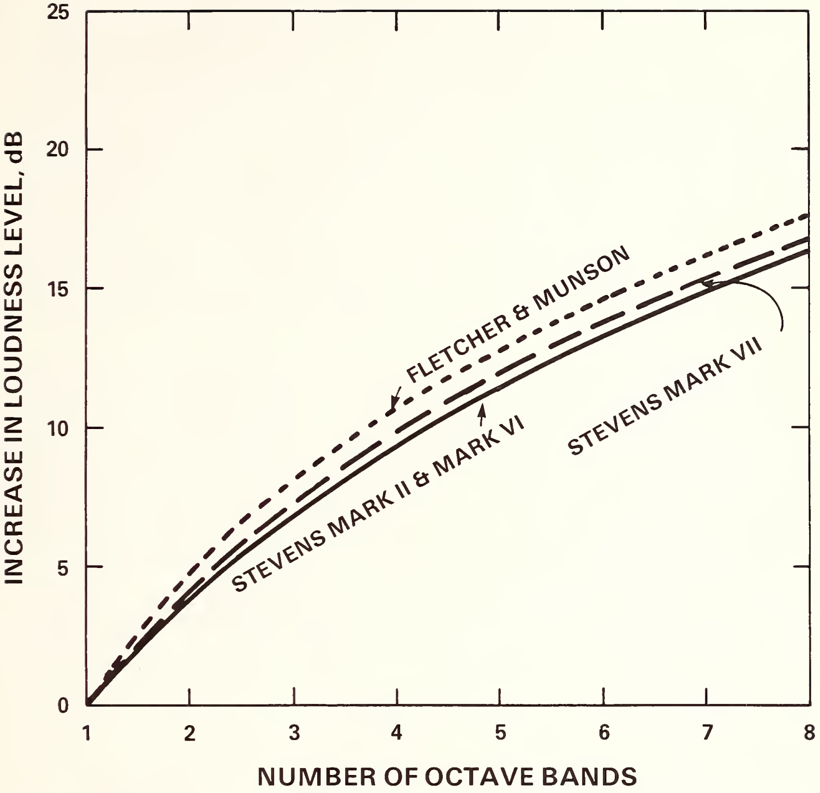

Figure 8. Increase in loudness level with increase in number of octave bands, when each octave band, taken alone, has the same loudness level.

which computational procedure is used to compute the loudness level.[3/] Thus the fact that van den Eijk did not sum the estimated loudness of the individual bands means that the equivalent loudness level in the receiving room might reach 36 to 38 phon even though the contribution from each band did not exceed 20 phon.[4/]

Moreover, while it is reasonable to assume that one cannot be annoyed by a noise that cannot be heard, it is an entirely different matter to assume that one cannot be annoyed by a noise heard at a low or moderate level (e.g., 36 to 38 phon). It has been argued [25-27,92] that loudness may not be an adequate predictor of annoyance or "noisiness". Thus, it might be argued that van den Eijk's requirements may have been derived through the use of an inappropriate descriptor. To test this possibility van den Eijk's published data and his rationale were used in conjunction with the 0.16-noy contour [93] rather than the 20-phon contour. (The reason for choosing the 0.16 noy contour was that it also corresponds to a sound pressure level of 20 dB, re 20 Pa, at 1000 Hz.) The curve corresponding to the 0.16 noy contour was compared to the curve derived by van den Eijk for the 20 phon loudness contour. The result is presented in Figure 9.

Inspection of Figure 9 suggests that the isolation values "required" on the basis of the Fletcher-Munson loudness differ from those based upon perceived noisiness, which in the context of Kryter's work is synonymous with annoyance, both in terms of the frequency range to be considered and the actual levels required. While the use of the Fletcher-Munson loudness curve suggests that the isolation required is independent of frequency in the range between 800 and 1600 Hz, the noisiness curve leads to isolation requirements that increase as a function of frequency in this range. The practical implication of this finding is that isolation requirements in building codes should be specified up to at least the 3200 Hz band, in contrast to van den Eikj's conclusion that isolation requirements need not be specified beyond the 800 Hz band. In addition, Figure 9 reveals that in the range below 400 Hz significantly more isolation is required than is suggested by van den Eijk's curve.

[3/] Note that the summation procedure of Fletcher and Munson applies only to pure tones; consequently, in order to estimate the overall loudness level associated with van den Eijk's spectrum each octave band was replaced by a single pure tone located at the band center frequency.

[4/] While loudness calculation procedures may not be accurate in predicting the growth of loudness as the bandwidth increases to eight octaves, it seems evident that the loudness will be considerably greater than that of a single octave band.

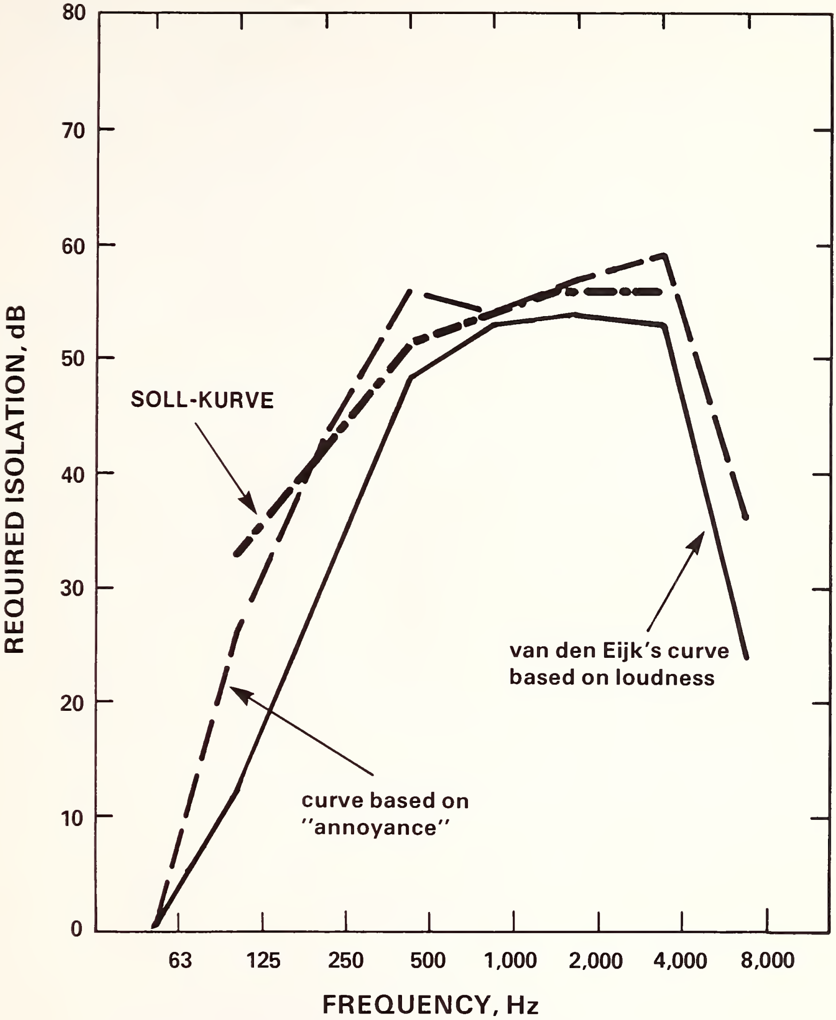

Figure 9. Noise isolation requirements based on loudness versus those based on annoyance, both compared with German Soll-Kurve (see text).

In addition to the problem of using loudness level as a criterion for generating noise isolation requirements, another difficulty exists. Inherent in van den Eijk's conclusions is the assumption that a solution to the problem of a neighbor's radio is a general solution for all noises. Although in subsequent studies van den Eijk [94] also examined the isolation required for television programs, isolation that is sufficient for television or radio programs might not be adequate for noises that have different spectral shapes. The British surveys clearly demonstrate that people in dwellings are disturbed by other types of noises -- such as the sounds from musical instruments. These sounds contain energy in regions other than those between 400 and 3200 Hz. Certainly in a country where modern stereo systems, household appliances, and home tools are common, requirements based upon the loudness of a neighbor's radio programs could be misleading. Furthermore, van den Eijk did not take into account other factors such as the preferred output level for radio or television programs, the location of the radio or television with respect to the party wall, or the background noise in the receiving room.

Northwood [95] has used an approach somewhat similar to that of van den Eijk to estimate noise isolation requirements for party walls. In his studies he combined the spectra of sounds from television, radio, speech, and domestic appliances. He also pointed out that this "standard household noise" must "compete" on the quiet side of the partition with the existing background noise. In the absence of data on ambient noises in homes, Northwood assumed a background noise with a spectrum similar in shape to the NC-25 contour [51]. Isolation requirements were then derived on the basis of the "standard household noise" intruding next door and being heard above this background noise. A curve of isolation as a function of frequency was thus obtained. This curve is reproduced in Figure 10, where it is compared to the German Soll-Kurve. Northwood states that the calculated isolation requirement shown in Figure 10 probably corresponds to about a 50 percent probability of intrusion. To get down to a reasonable value, say 10 percent to 20 percent, would require that the sound insulation be raised perhaps 5 dB. Thus, it appears that the German grading curve . . . is about the right shape and not far from the right level." It might be noted, however, that Northwood's isolation requirements fall off at frequencies above 1000 Hz, while those in the German grading curve do not.[5/]

[5/] Note, however, that it is relatively simple to build partitions with adequate transmission losses at high frequencies, provided that they are well-sealed. Thus, the shape of the grading curve at high frequencies may have little practical significance.

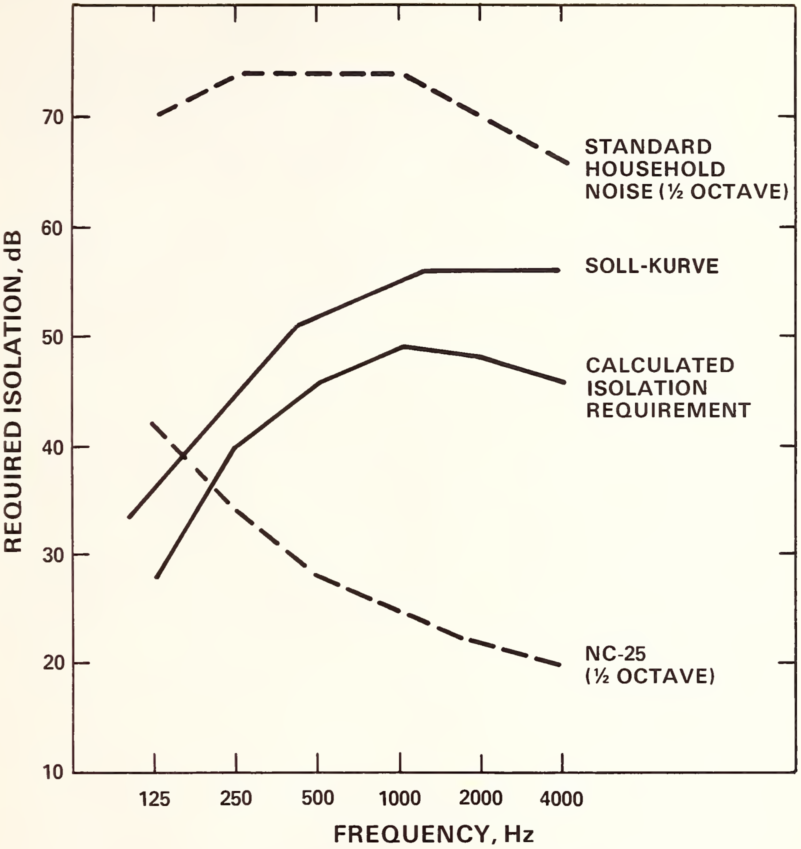

Figure 10. Noise isolation required to reduce "standard household noise" to a level, in the receiving room, corresponding to an NC-25 contour [96].

Northwood points out that the noise isolation requirements developed are rather speculative. This is so because:

(1) Data regarding the distribution of indoor noise levels are limited and thus Northwood's standard household noise may or may not be representative of typical households.

(2) There are no data regarding the relation between the NC-25 contour and actual household noises, and thus the NC-25 contour may or may not be a reasonable way to define ambient noise in dwellings. It is known that spectra that meet NC contours are judged "hissy", "rumbly", and unnatural [46]. Consequently, it is questionable whether they represent typical background noises.

In 1969 Clark [96] carried out a series of psychoacoustic studies designed to test the validity, from a human response viewpoint, of the shape of the rating curve embodied in the ISO and ASTM standards as well as to examine the need for the "8 dB" rule (described in Section 3.2.1). In one series of experiments, subjects were exposed to three different "noise" sources -- male speech, popular music, and vacuum cleaner noise. Each source was presented alternatively through one of two filters -- one representing the shape of the ASTM rating contour (STC) and the other being a one-third octave or octave band-pass filter. The stimuli were presented in a background noise conforming to the spectrum shape and level of the NC-25 contour. Subjects were asked to adjust the level of the comparison band of noise until it was judged to be equal in annoyance to the test noise passing through the "STC filter". The results of these experiments showed that when subjects equated the "annoyance" of a one-third octave or an octave band of noise to that of the same noise passing through the "STC" filter, they were in fact approximately tracing an inverted STC contour. This finding was interpreted as an indication that the shape of the STC contour is indeed representative of the relative contributions of the various bands of noise to annoyance.

However, the study may not adequately solve the problem of the shape of the grading curve for the following reasons:

- Since the subjects were always judging the one-third or octave band of noise against an STC contour the results could have been biased towards the STC contour due to attentional effects.

- Inherent in Clark's experimental design was the assumption that household ambient noise is adequately represented by an NC-25 contour. This contour may or may not represent appropriate conditions. The annoyance produced by an intruding noise is dependent upon the signal-to-noise ratio (i.e., the ratio of intruding sound to background noise in receiving room); thus the shape of the background noise spectrum may be critical.

- The range of sound levels in Clark's study was limited to levels that were just perceptible above the background noise. Accordingly, generalization to other situations may be questionable.

In a second series of experiments, Clark [96] addressed the question of the importance to human observers of coincidence dips in a transmission loss curve. The experiment was carried out in a manner similar to the one described previously, but the band-pass filter was replaced with a filter corresponding to the noise isolation between two rooms. The filter also simulated coincidence dips, either one-third octave or an octave in width and 0 to 20 dB in depth. Subjects were asked to adjust the attenuation of the noise passing through the STC filter until it was as annoying as the same noise passing through the simulated noise isolation filter. The results of this series of experiments suggest that dips in the noise isolation are not very important subjectively. Thus, the 8 dB rule present in the STC rating scheme may not be necessary. However, these results should also be interpreted cautiously since some of the same uncertainties described above are applicable to this second set of experiments.

3.2.4. Conclusions Concerning the Grading Curve

The previous discussion indicates that, although precise and well-defined rules exist for rating building elements with respect to their ability to provide sound insulation, the human response data upon which these requirements are based are inconclusive.

While the social surveys conducted in England and Sweden appeared, at least superficially, to demonstrate that the traditional 9-in plastered brick wall leads to a minimal rate of complaints among residents, the French survey tends to demonstrate that such walls may not provide sufficient protection. In addition, since all the surveys reviewed employed a very limited range of insulation, and since none considered any structure significantly better with respect to insulation than the 25-cm brick wall, it is impossible to extrapolate from these surveys how people would respond to walls with either superior insulation capabilities or different characteristics.

The evidence based upon subjective response (e.g., loudness or annoyance) is even more sketchy, and highly speculative. It is therefore not surprising that, over the years, numerous reference curves have been used for rating noise insulation and that, as shown in Figure 11, these curves vary somewhat with respect to shape, frequency bounds and the extent of insulation required. Since there is a scarcity of data as to what constitutes subjectively significant changes in household noise intrusions, it is difficult to estimate the significance of the differences observed among the curves.

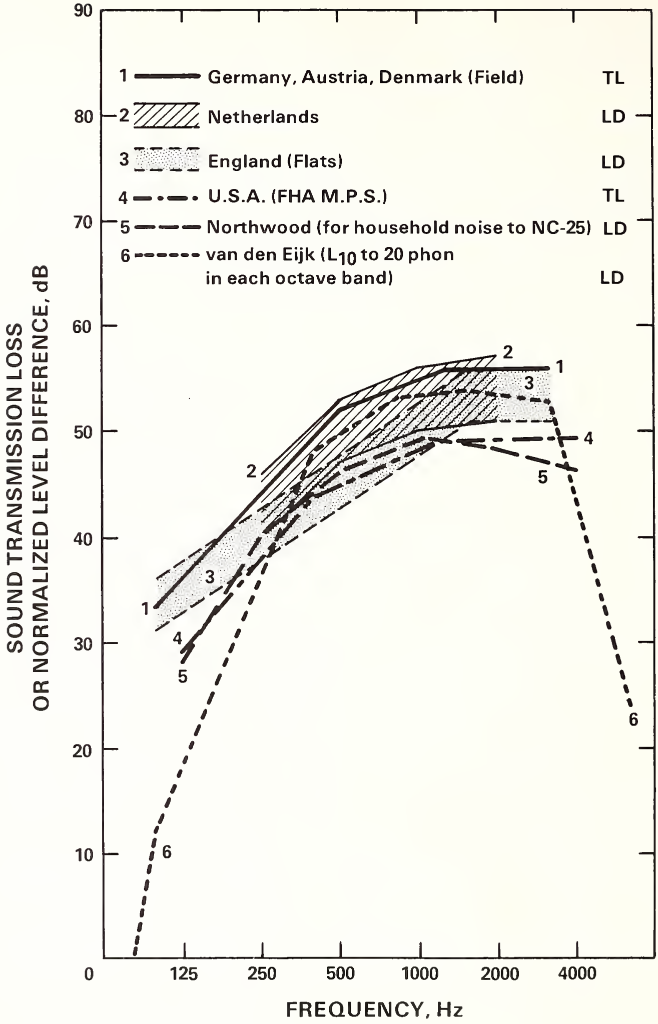

Figure 11. Comparison among several reference curves used or proposed for use in rating partitions.

The curves based upon loudness (or annoyance) also imply that the ISO and ASTM curves may be too stringent at low and high frequencies. While good transmission loss is easy to achieve at high frequencies (provided that no large coincidence dip exists), it is both difficult and expensive to achieve good isolation against low-frequency sounds. Therefore, from a design standpoint, it would be desirable if isolation requirements could be relaxed at low frequencies, as implied by the curves derived on the basis of loudness. However, such a recommendation may be premature given the limited data base.

To conclude, international and national standard curves exist against which partitions can be judged. However, unresolved questions remain regarding the shape of the grading curve, the frequency region of concern, the significance of deviations from the grading curve, the importance of coincidence dips, and, most importantly, the adequacy of the grading curve in terms of meeting human requirements. On the basis of current knowledge, answers to these unresolved questions cannot be given.

3.3. Weighted Level Differences

An increased interest is evident in the single values obtained when sound levels (e.g., A-weighted or C-weighted) are measured in both the source and the receiving room. This trend is a reaction to the substantial data requirements necessary to make measurements of noise isolation and sound transmission loss in narrow (e.g., one-third octave) bands.

In 1965 Gosele [97] and Gosele and Bruckmayer [98] noted that high correlations exist between partition ratings based on the ISO procedure (see Section 2) and ratings based on the difference between the A-weighted sound level in the source room and the A-weighted level in the receiving room. These observations were confirmed experimentally by Gosele and Koch [99], Fuchs [100] and Harman [101]. Similar agreements have also been noted for outdoor-to-indoor noise reductions by Scholes and Parkins [102].

These observations led Siekman, Yerges and Yerges [103] to propose a simplified field sound transmission test for partitions based on an A-weighted level difference. Quindry and Flynn [104] and Flynn [105] have also demonstrated a good correlation between ratings based on level differences and those derived from the "ASTM/ISO procedures"[6/]. Their analyses indicate that the best correlations with the Noise Isolation Class are obtained when C-weighted sound level is used in the source room and an A-weighted level is used in the receiving room.

[6/] That is, those procedures whereby the grading curve is fitted to the measured data in accordance wth the American [85] or International [84] standards.

Donato [106], in a study on insulating houses against aircraft noise, found good agreement between Sound Transmission Class and the difference between the outdoor and indoor Perceived Noise Levels.

In all of the above investigations, good agreement was observed between ratings based on weighted level differences and those obtained using the ISO/ASTM procedure. In addition, there appears to be a consensus among all the above researchers (except Donato) regarding the desirability of using the A-weighted level in the receiving room. A similar consensus, however, does not exist with respect to the weighting function to be used in the source room, since some investigators advocate the use of an A-weighted level while others advocated the use of the C-weighted level.

All the proposals reviewed above were based upon the high correlation obtained between ratings based on level differences and those based on the ASTM/ISO methods (and therefore traceable to the grading curves contained in the ASTM and ISO standards).[7/] In view of the lack of evidence regarding the validity, from a human response viewpoint, of the ISO and ASTM rating methods, the observed correlations of these schemes do not, in themselves, justify the adoption of level-differences in building codes.

With respect to typical household noises, we support the view of Schultz [107], who thinks it is not necessary to demonstrate high correlation between level differences and other rating schemes, since an A-weighted level difference has as much independent claim to validity as that of the STC procedures.

[7/] Note that a large portion of the good correlation among rating schemes arises because of the fact that if a noise isolation (or sound transmission) versus frequency curve is shifted by X dB, all of the ratings also shift by X dB.

4. ISOLATION RATINGS FOR BUILDINGS: DEPENDENCE UPON INDOOR NOISE CRITERIA AND UPON SOURCE SPECTRUM

In the course of the present study, computations were performed to illustrate how various requirements for rating noise isolation result from alternate choices of procedures for rating the indoor noise environment.

Further calculations (see Section 3.2.3) were made using a spectrum (octave band levels that were exceeded ten percent of the time) from van den Eijk's study [92] of radio programs. Two attributes of human response and several computational procedures were examined. "Loudness" was computed using the procedures of Fletcher and Munson [4], Stevens' Mark VI [12,30], and Stevens' Mark VII [14]. "Noisiness" was computed using Perceived Noisiness, as now standardized [72]. Computations were also made using the A-weighted sound level.

For each procedure used to rate the noise in the receiving room, computations were made of the isolation required, as a function of frequency, for each octave band to contribute equally to the rating of the noise environment -- i.e., so that the contribution to loudness, "noisiness", or A-weighted level of each octave band would be the same. In order to tie the five schemes together, the isolation was computed for the "loudness", "noisiness", or A-weighted level in the receiving room predicted to be judged equivalent to an octave band of noise centered at 1000 Hz and having a sound pressure level of 40 dB re 20 μPa.

The results of these computations are shown in Figure 12. It can be seen that, depending upon the scheme used to rate the noise environment in the receiving room, curves of isolation versus frequency are derived which differ with respect to both frequency dependence and the magnitude of isolation required to yield a noise environment that is "equivalent" to the 1000 Hz octave band of noise used as a reference sound. Specifically, if the A-weighted level is used to rate the receiving room spectrum, the criterion for isolation specifies a much lower level than for either loudness or noisiness. This occurs because the perceived magnitude of broad-band noise increases more rapidly with bandwidth than does the A-weighted sound level.

In order to examine further the effect of the rating scheme (for the receiving room noise) on the spectral shape of the required isolation curve, a number of similar computations were carried out for other noise spectra commonly found indoors and outdoors. The indoor spectra used in these computations are shown in Figure 13, and the outdoor spectra in Figure 14. With these spectra, the isolation required was derived so that each one-third octave band would contribute equally to each of several rating schemes for the receiving room spectrum. Specifically, the isolation required in each one-third octave band was computed so that the shape of the receiving room spectrum would conform to a PNC-35 contour, a 1 sone contour (Mark VII), a 1 noy contour, or an inverted A-weighting contour (these contours are shown in Figure 15).

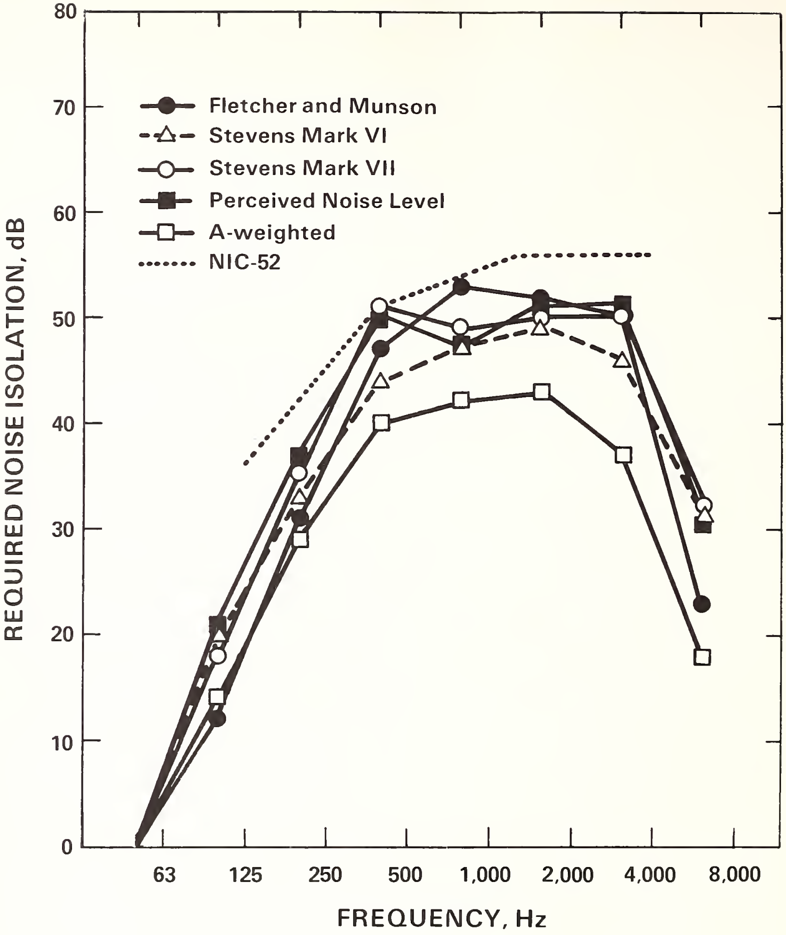

Figure 12. Noise isolation required in order that the sound in the receiving room, due to radio programs in the source room, shall not produce, for more than ten percent of the time, a computed sensation in excess of that produced by an octave band of noise centered at 1 kHz and having a sound pressure level of 40 dB (re 20 μPa). The several curves correspond to the use of different procedures to rate the noise environment in the receiving room.

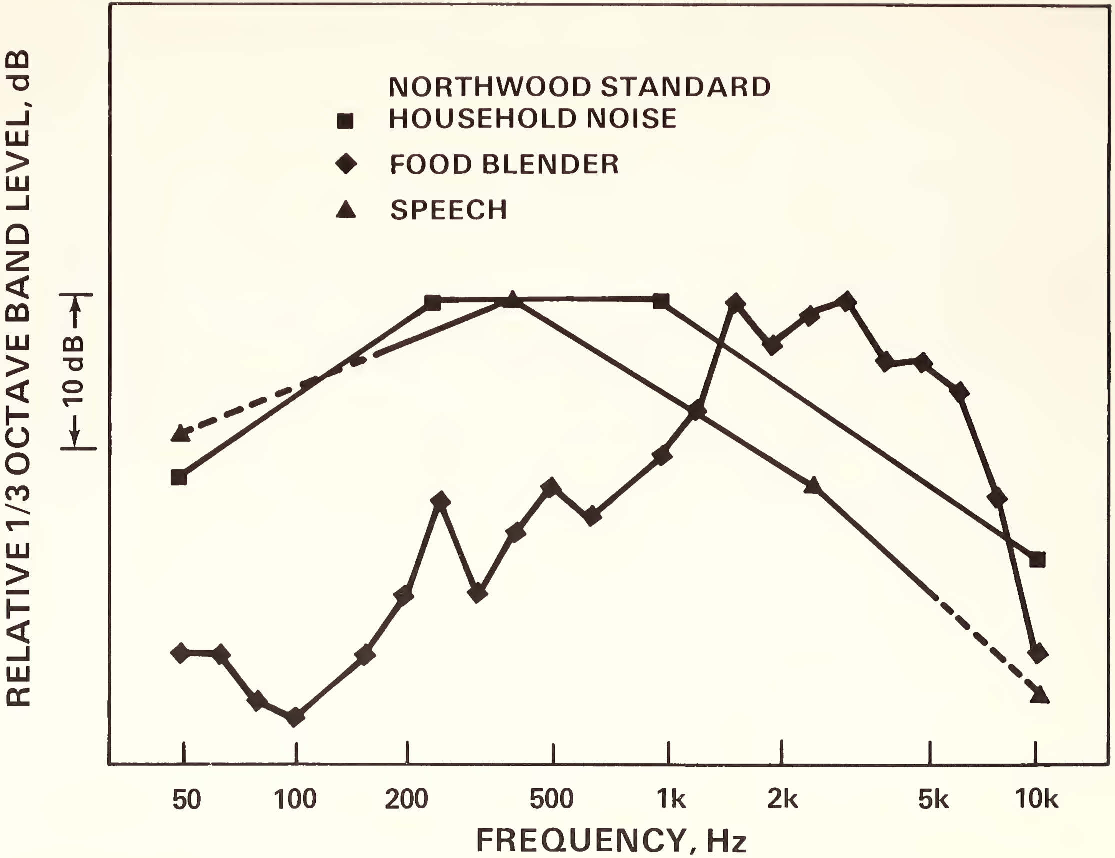

Figure 13. Normalized spectra of selected indoor noise sources.

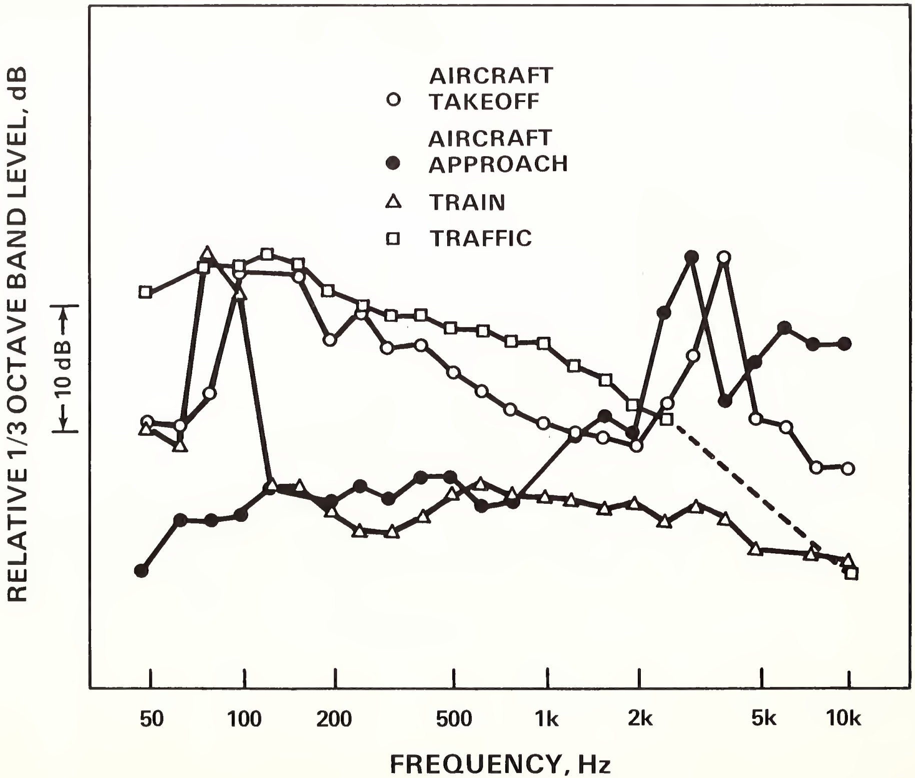

Figure 14. Normalized spectra of selected outdoor noise sources.

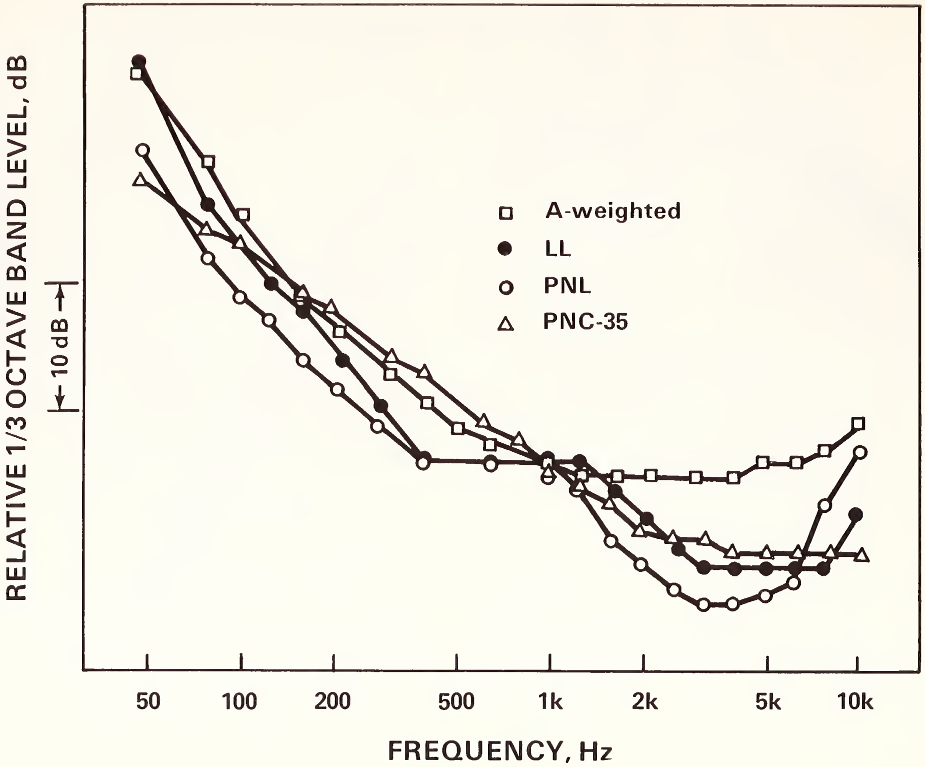

Figure 15. Alternative receiving room spectral shapes used to derive noise isolation curves for the various noise sources shown in Figures 13 and 14 (see text).

In these analyses, only the shapes of the isolation curves were examined. For this comparison, all of the curves were normalized to a common ordinate value at 1000 Hz. The shapes of the isolation curves needed to maintain the desired spectral shapes in the receiving room are shown in Figures 16, 17, and 18 for three different source room noises (Northwood's household noise, average speech spectrum, and a food blender, respectively.)

For household noise and speech, the computed requirements for isolation above approximately 1000 Hz do not increase as rapidly with frequency as does the actual isolation that can be obtained with typical party walls commonly found between dwelling units. Thus, unless an unusually severe coincidence dip exists in the noise isolation in the frequency range above 1000 Hz, the overall rating for the noise isolation between spaces would be governed by the isolation in the frequency range from only 125 to 500 Hz approximately.

On the other hand, for a source having a spectrum such as that shown for the food blender, the overall rating of noise isolation would often be governed by the performance only between 1600 and 4000 Hz, particularly if there were a coincidence dip in this region. With the possible exceptions of food blenders (which typically have a very short duty cycle) and vacuum cleaners, few indoor noise sources appear to have sufficiently high levels at frequencies above 1600 Hz to constitute a serious problem in a neighbor's dwelling. Thus, from a practical point of view, ratings for the noise isolation between dwelling units would usually be governed by the performance at frequencies below about 1000 Hz.

For source room spectra such as those shown in Figure 13 for Northwood's household noise and speech, the frequency dependence of the isolation required (see Figures 16-17) to attain any of the four spectral shapes in the receiving room (see Figure 15) is generally similar in shape to the ASTM contour and to the A-weighting contour. Thus for such spectral shapes it would appear to be reasonable to rate isolation in terms of the ASTM contour [84] or to rate isolation in terms of A-weighted level differences [107].

If the source spectra contained considerably more high-frequency energy than the spectra of "household noise" and speech, the isolation ratings might differ significantly, depending upon the grading curve used. For such sources a choice among various human response criteria (based upon loudness, noisiness, etc.) could be quite crucial. For example, deficiencies in high frequency isolation would affect a rating based on the Perceived Noise Level more than it would a rating based upon, say, A-weighted sound level.

For outdoor spectra the isolation curves derived to maintain the indoor noise intrusion spectrum along a PNC-35 contour, a 1-noy contour, a 1 sone contour, and an inverted A-weighting contour are shown in Figures 19, 20, 21, and 22 for each of the outdoor spectra shown in Figure 14.

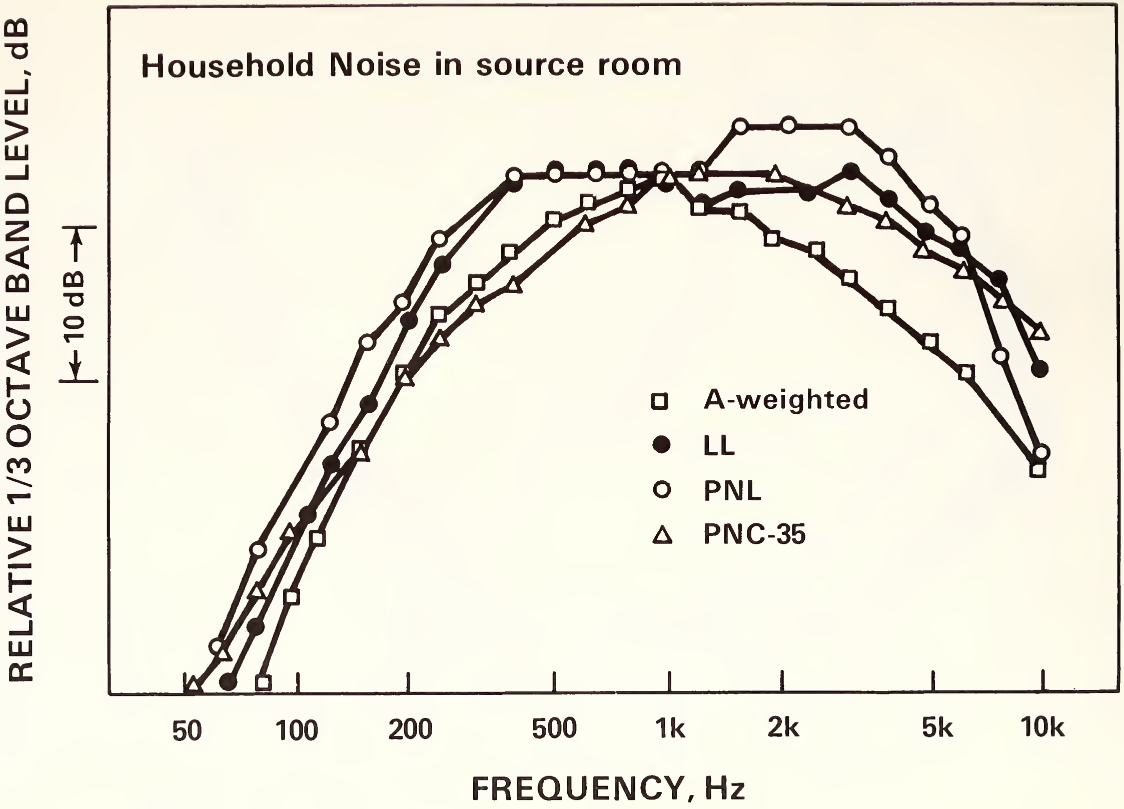

Figure 16. Shape of noise isolation curves required, for standard household noise, to maintain in the receiving room the spectral shapes shown in Figure 15.

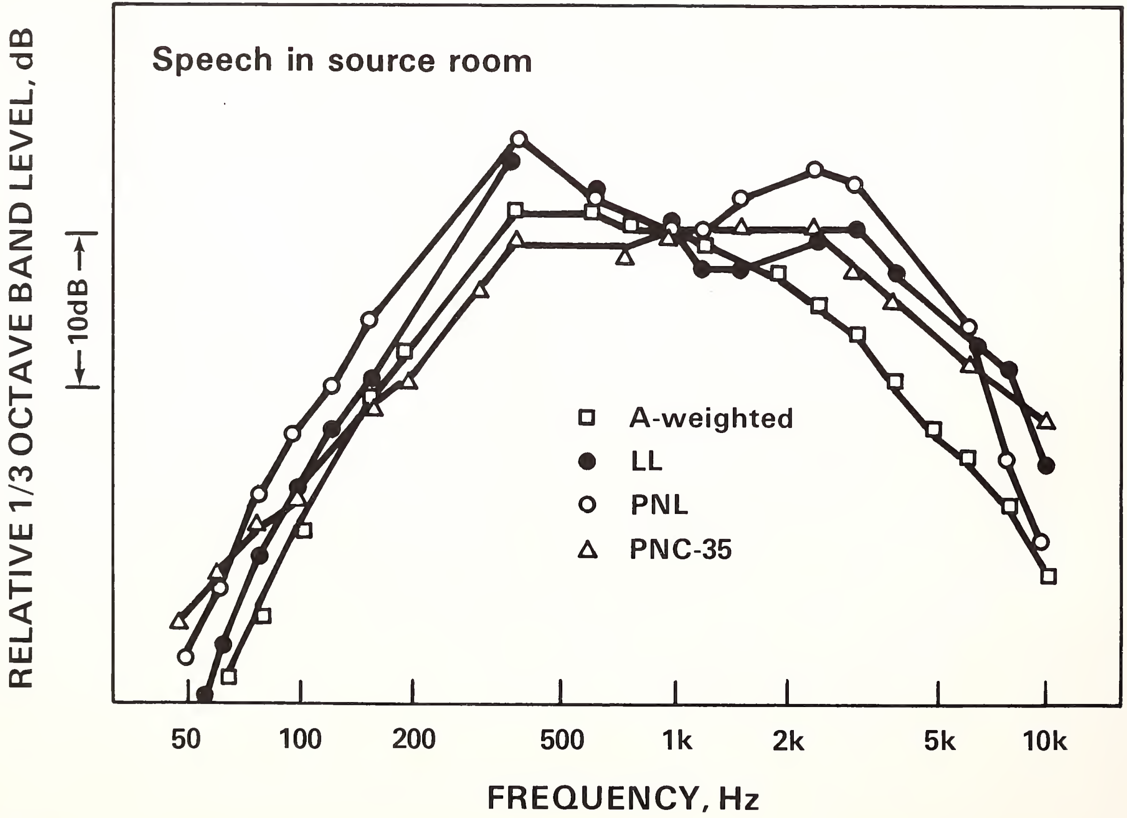

Figure 17. Shape of noise isolation curves required, for average speech spectrum, to maintain in the receiving room the spectral shapes shown in Figure 15.

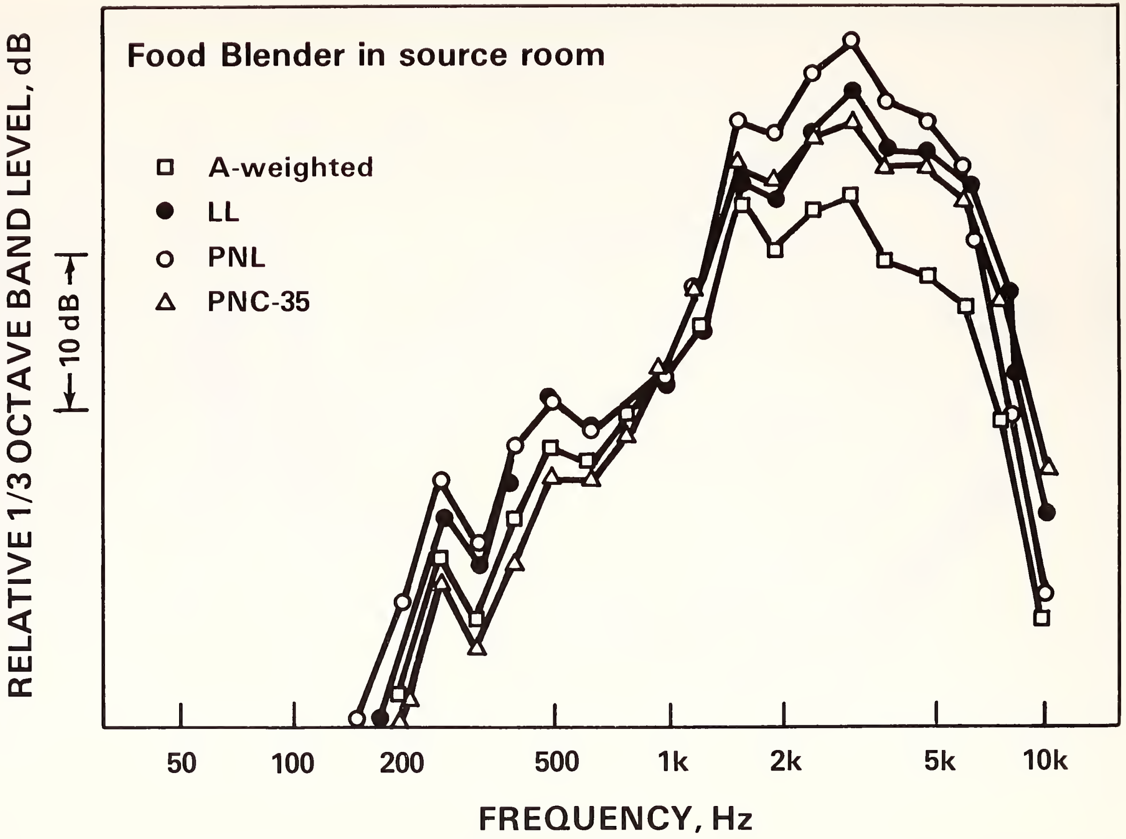

Figure 18. Shape of noise isolation curves required, for food blender, to maintain in the receiving room the spectral shapes shown in Figure 15.

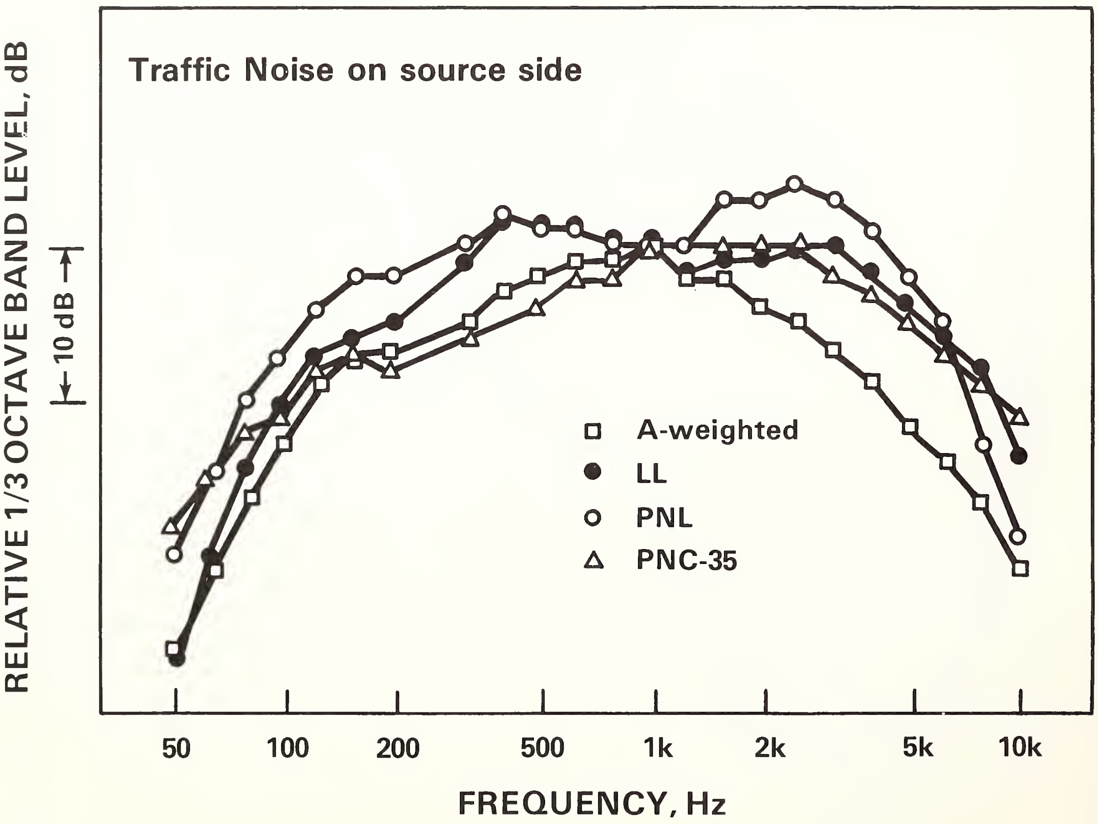

Figure 19. Shape of noise isolation curves required, for traffic noise, to maintain in the receiving room the spectral shapes shown in Figure 15.

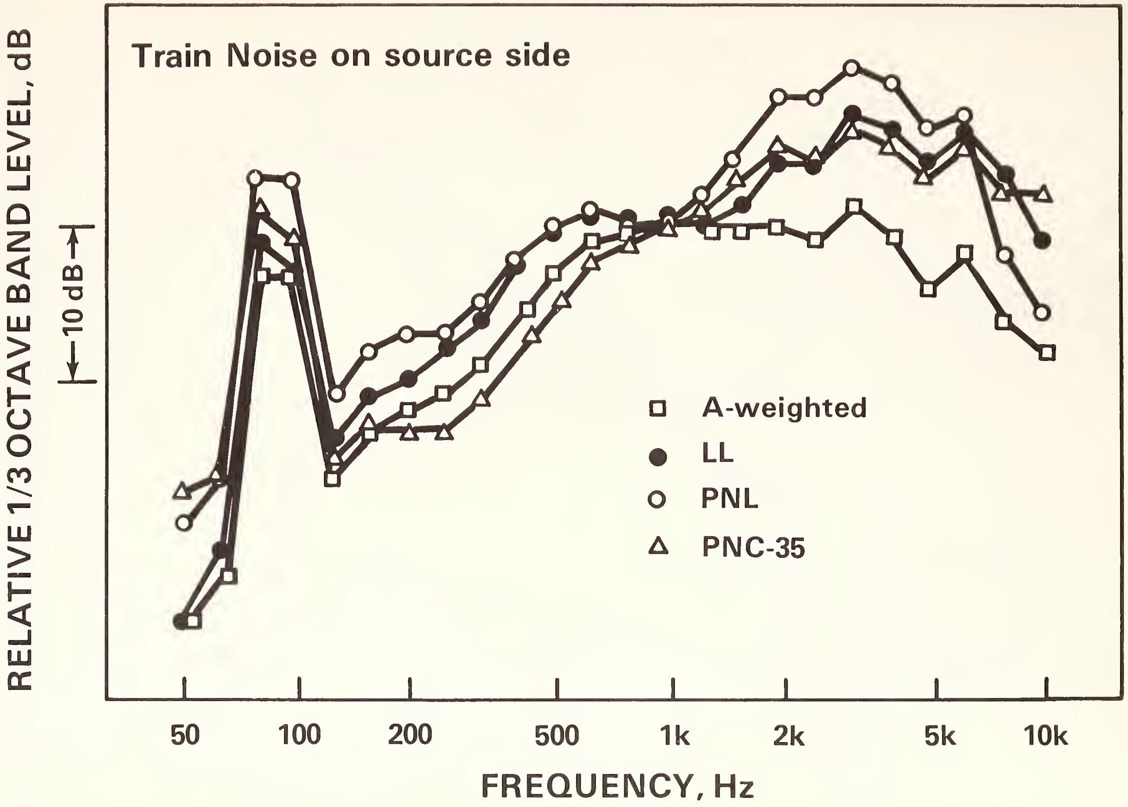

Figure 20. Shape of noise isolation curves required, for train noise, to maintain in the receiving room the spectral shapes shown in Figure 15.

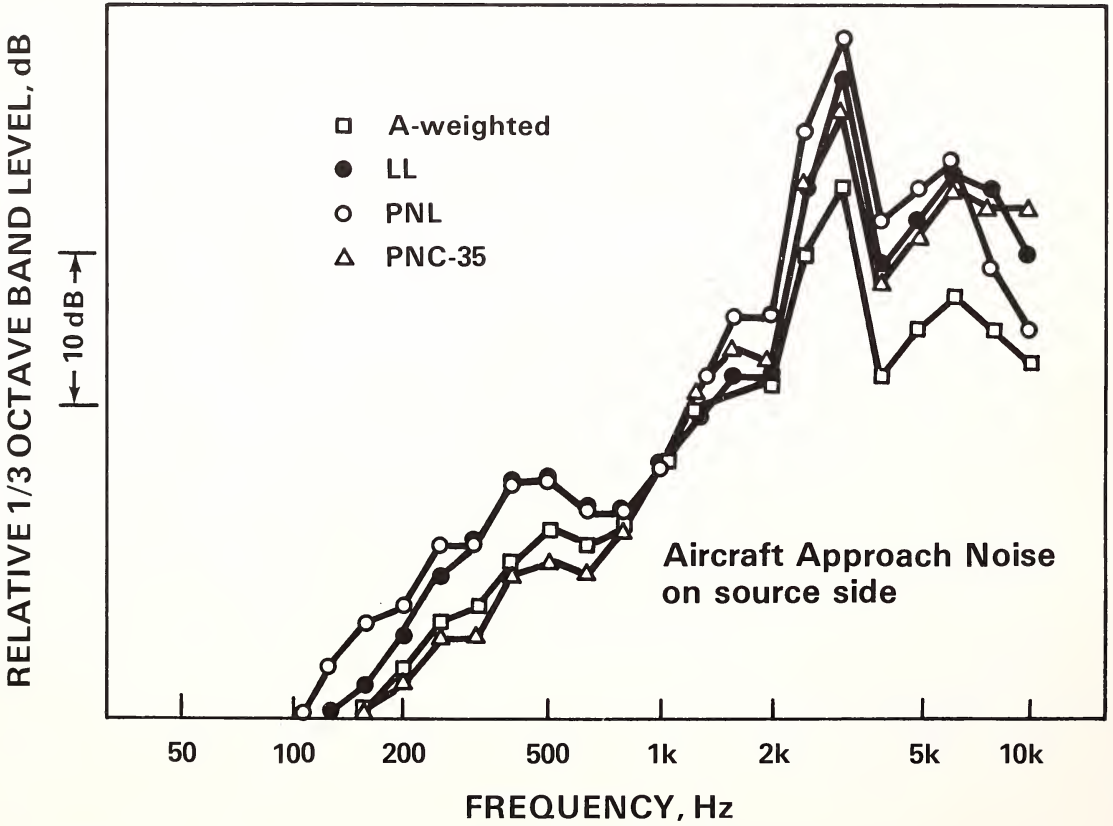

Figure 21. Shape of noise isolation curves required, for aircraft approach, to maintain in the receiving room the spectral shapes shown in Figure 15.

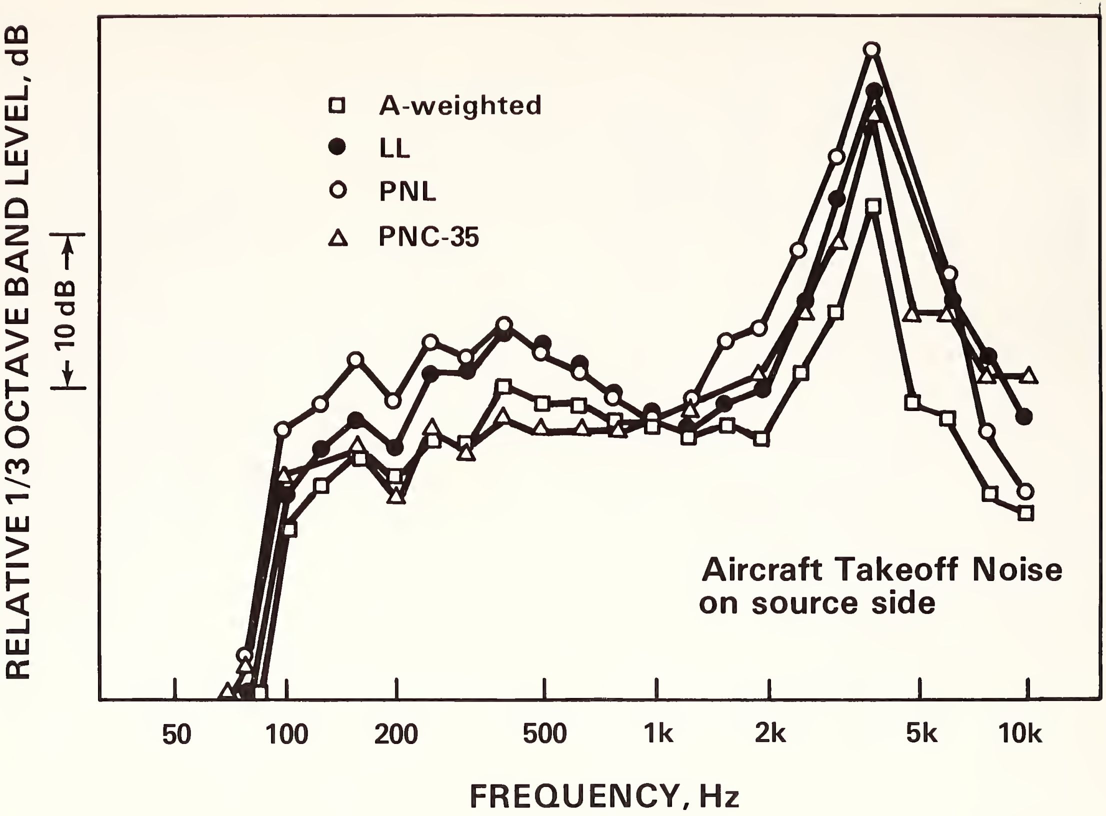

Figure 22. Shape of noise isolation curves required, for aircraft take-off, to maintain in the receiving room the spectral shapes shown in Figure 15.

These figures show that when the outdoor noise source has significant high-frequency components (e.g., a large turbofan aircraft on approach), the indoor noise spectrum will be dominated by this frequency region. A rating based upon either loudness level (Mark VII) or noisiness (PNL) would emphasize this high frequency region more than one based upon either a PNC contour or an inverted A-weighting contour.

When outdoor noise spectra are similar in shape to typical household noise (e.g., traffic noises), an inverted A-weighted contour would suggest noise isolation requirements generally similar to those derived on the basis of loudness or noisiness. When the outdoor noise source produces significant low frequency noise (e.g., train noise), the interior noise contains considerable low-frequency energy, e.g., in the 50 to 125 Hz region. For such spectra, a rating based upon noisiness would emphasize these low frequencies more than the other curves considered.

For the present it appears that most outdoor sources of noise will be regulated in terms of A-weighted levels. Since noise sources having various frequency distributions will contribute to the interior noise, ratings of outdoor-to-indoor isolation should take into account differences among source spectra. For example, isolation requirements (for the building envelope) based on an A-weighted level difference measured for traffic noise would be inappropriate for either train or aircraft noise.

5. SIGNIFICANCE OF TEMPORAL VARIATIONS ON BUILDING NOISE RATING PROCEDURES

Human response to noise is substantially affected by temporal variation of the sound level and frequency spectrum of the noise. None of the schemes proposed, or incorporated into building codes, have attempted to account for this factor. For this reason, regardless of which scale is utilized to rate the interior environment, consideration must be given to the need for a cumulative measure of noise which appropriately accounts for its time variation.

Recently, the Environmental Protection Agency has proposed [69,108] the Day-Night Average Level (L_{dn}) for describing the noise environment, both outdoors and indoors. Although it may be premature to generalize methods developed from studies of outdoor environments to the assessment of interior environments, the method does appear promising. For this reason an initial exploration of some of the implications of L_{dn} with respect to outdoor-to-indoor required isolation was conducted. Similar computations could be carried out for various cumulative noise measures such as the Noise Pollution Level and the Traffic Noise Index.

To perform the analyses described below it was arbitrarily assumed that a house is located 60 meters away from a freeway, 15 meters away from a railway and in proximity to an airport, with aircraft overflights at an altitude of 300 meters. One-third octave band Single Event Noise Exposure Levels were assumed for average passbys of each type of noise source, as were average traffic densities for each hour (see Figure 23). From these data one-third octave band hourly average noise levels (L_{eq}) at the facade of the dwelling were computed. The results were then utilized to derive the isolation required so that the one-third-octave band hourly average level inside the dwelling would conform to a PNC-35 contour.

From these detailed spectral data, A-weighted hourly average level differences were computed. Representative data are presented in Table 3 where it can be seen that the A-weighted level differences (e.g., isolation required to maintain PNC-35 indoors) varied from a low of 10 dB during the quietest hour of the night (0200), (when there were no trains or planes) to a high of 30 dB (1300) during the period of high traffic activity.

The average A-weighted isolation required to maintain a PNC-35 indoor (or approximately an A-weighted level of 43 dB) throughout the daytime period (0700-2200 hours) was 27 dB. This isolation requirement dropped to 22 dB for the nighttime period (2200-0700 hours). However, when the Day-Night Average Level was computed, the 10 dB night penalty caused the average isolation requirement to exceed 30 dB. This is equivalent to having required the nighttime interior level to drop to about a PNC-25 (or an A-weighted level of approximately 34 dB). A summary of these data is presented in Figure 23 in terms of A-weighted level differences. The upper part of Figure 23 shows the corresponding traffic densities.

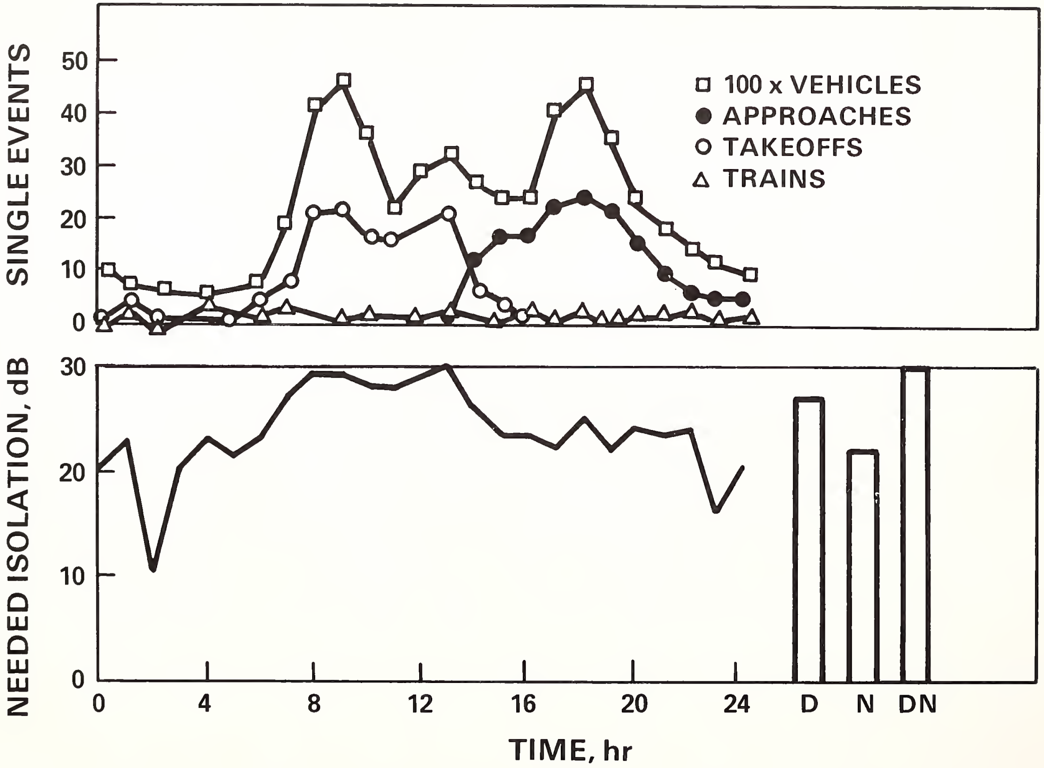

Figure 23. Hourly average A-weighted level differences required to maintain an indoor noise environment corresponding to a PNC-35 contour (approximately an A-weighted Day-Night Average Level of 45 dB) for the hourly traffic densities shown in the upper figure (see text).

Table 2. Outdoor-to-Indoor Noise Isolation Required (in dB) to maintain a PNC-35 or an L_{dn} of 45 dB Indoors as a Function of frequency and of Time of Day.

Center Frequency of Third Octave Band, Hz	Time of Day (hour)							Daytime 0700-2200	Nighttime 2200-0700	L_{dn}
	0200	0700	0900	1300	1800	2200	2400			
63	6	20	22	23	18	18	15	19	16	23
80	10	35	25	36	33	35	32	32	32	39
100	15	36	28	36	33	36	33	33	33	39
125	18	29	31	31	28	26	23	29	24	32
160	20	31	33	33	30	28	25	31	26	34
200	21	32	34	35	31	29	27	32	27	35
250	22	33	36	36	32	30	27	33	28	36
315	23	35	37	38	34	32	29	35	30	38
400	24	37	39	40	35	34	31	37	32	40
500	25	39	41	42	37	37	34	38	35	42
630	26	41	42	43	39	39	36	40	37	44
800	27	42	43	44	40	39	36	41	37	45
1000	27	43	44	45	41	40	37	42	38	45
1250	26	44	46	46	41	40	38	43	39	46
1600	25	45	47	48	42	40	38	44	39	47
2000	24	46	48	49	43	41	39	45	40	48
2500	22	44	46	46	40	39	37	43	38	46
3150	20	42	43	45	39	40	37	41	38	45
4000	18	41	41	43	37	38	35	39	36	43
5000	16	37	37	39	33	35	32	35	33	40
6300	12	37	33	38	34	37	34	35	34	40
8000	8	34	30	35	30	33	30	31	30	37
10000	4	32	25	32	29	32	29	29	29	35
A-weighted level	10	27	29	30	25	24	21	27	22	30

6. CONTRIBUTION OF OUTDOOR SOURCES TO THE INDOOR NOISE ENVIRONMENT

In the previous section, indoor noise levels were assumed to be entirely due to outdoor sources and the isolation requirements were computed accordingly. However, if indoor noise levels due to indoor sources exceed the selected indoor noise criteria, it might be argued that less isolation against outdoor sources is needed if they are already competing with the interior "ambient" noise levels due to, for example, heating and air conditioning systems, appliances, music, or conversation. However, unlike most outdoor noise sources many indoor sources are either totally or partially under the operator's control. For example, while one cannot control the noise emission from a vacuum cleaner one may choose not to use the device at a particular time. Moreover, one may choose to raise the level of desired sounds such as speech, radio, television, or stereo, so that they can readily be heard above the level of sounds intruding from outdoors. This may lead to the conclusion that the indoor source is primarily responsible for the interior noise environment while, in fact, the contribution from the indoor source was partially determined by the levels intruding from outdoors.

In order to explore the relative contributions of outdoor and indoor noise sources to interior noise levels, indoor and outdoor data obtained in an earlier EPA study [109] were analyzed in further detail. In this study, indoor and outdoor noise levels were measured simultaneously at 15 sites in urban residential areas, distant from any major outdoor noise sources (e.g., highway or airport). Although the EPA study included 15 sites, only 12 contained sufficient data for the present analysis. Noise measurements consisted of continuous monitoring and recording of A-weighted sound level on digital tape. From these data, hourly average sound levels (L_{eq}) were derived for each site, both indoors and outdoors. These hourly average levels provide the data for the analyses reported here.

Average sound levels were derived for daytime (0700-2200), nighttime (2200-0700), evening (1900-2200) and "late" night (0100-0500). The results of these calculations are presented in Figures 24-27, where each data point represents a site, and the average indoor sound levels are plotted versus the outdoor levels. The mean sound levels (e.g., arithmetic mean of the sound levels for the 12 sites), and the standard deviation about that mean, were also computed for each time period. In addition, the correlation coefficient between indoor and outdoor sound levels for each time period was determined. The results of these computations are summarized in Table 3.

Inspection of the entries in Table 3 reveals that at sites removed from any major outdoor noise source:

- the correlation between indoor and outdoor sound levels is weak, (0.3 or less) except during the late night hours, from 1 a.m. to 5 a.m., when the correlation coefficient is slightly better (0.54);

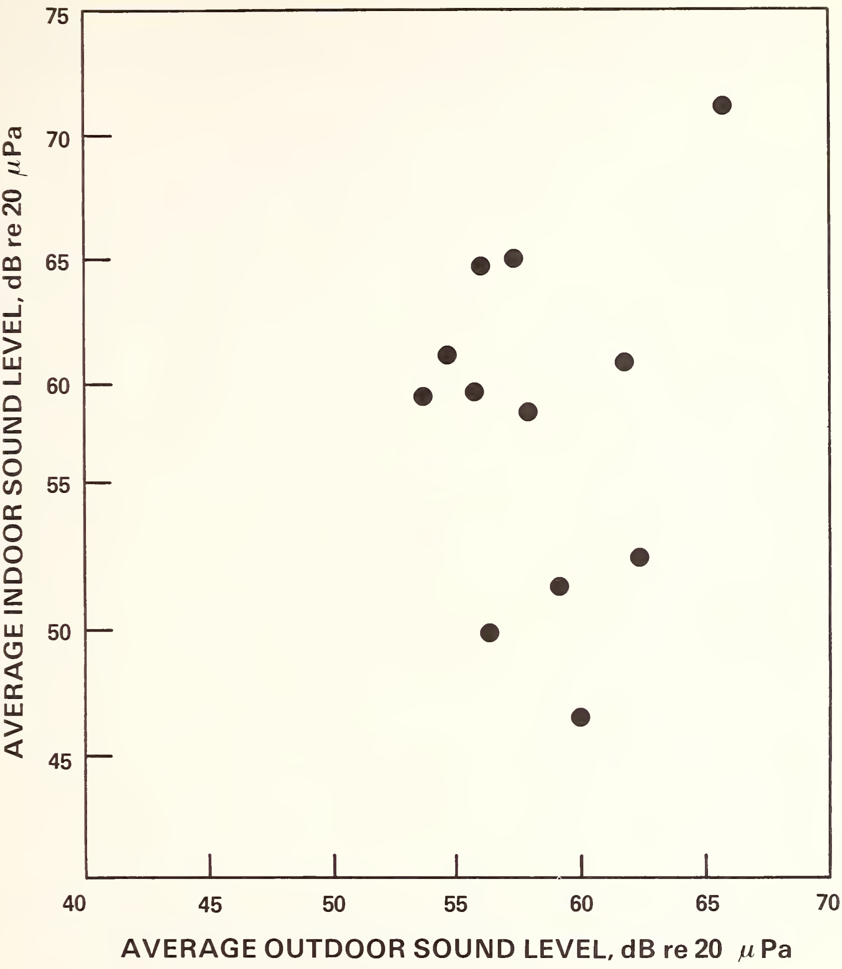

Figure 24. Daytime (0700-2200 hours) indoor versus outdoor average A-weighted sound levels (L_{eq}) for twelve sites.

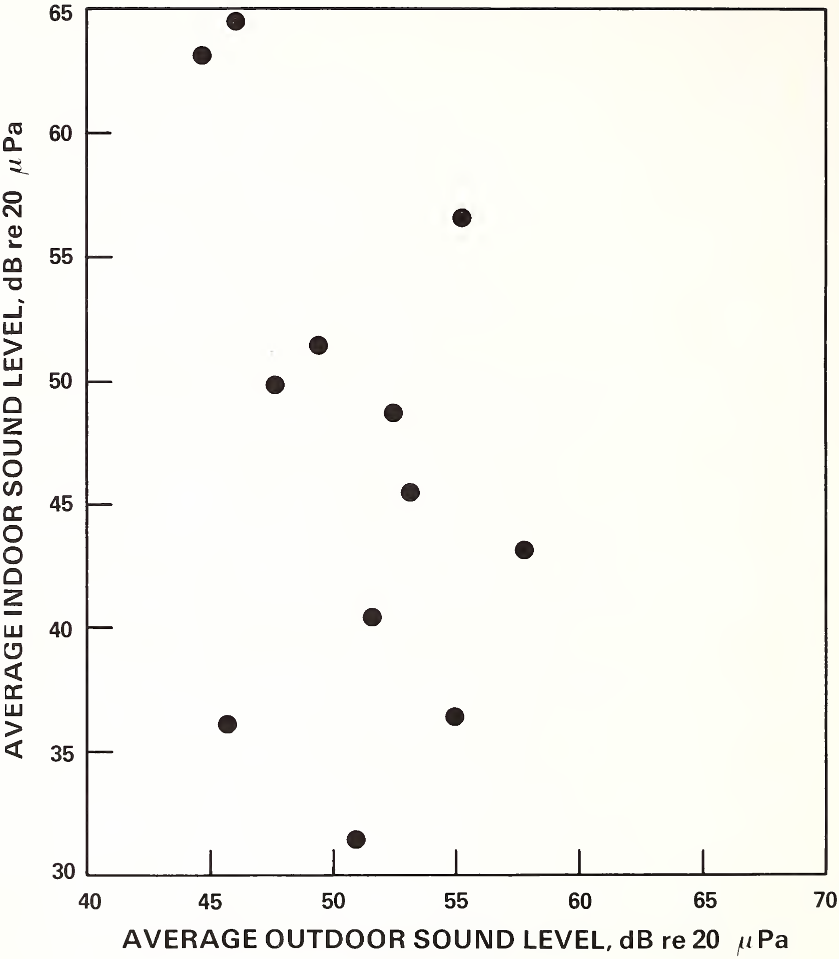

Figure 25. Nighttime (2200-0700 hours) indoor versus outdoor average A-weighted sound levels (L_{eq}) for twelve sites.

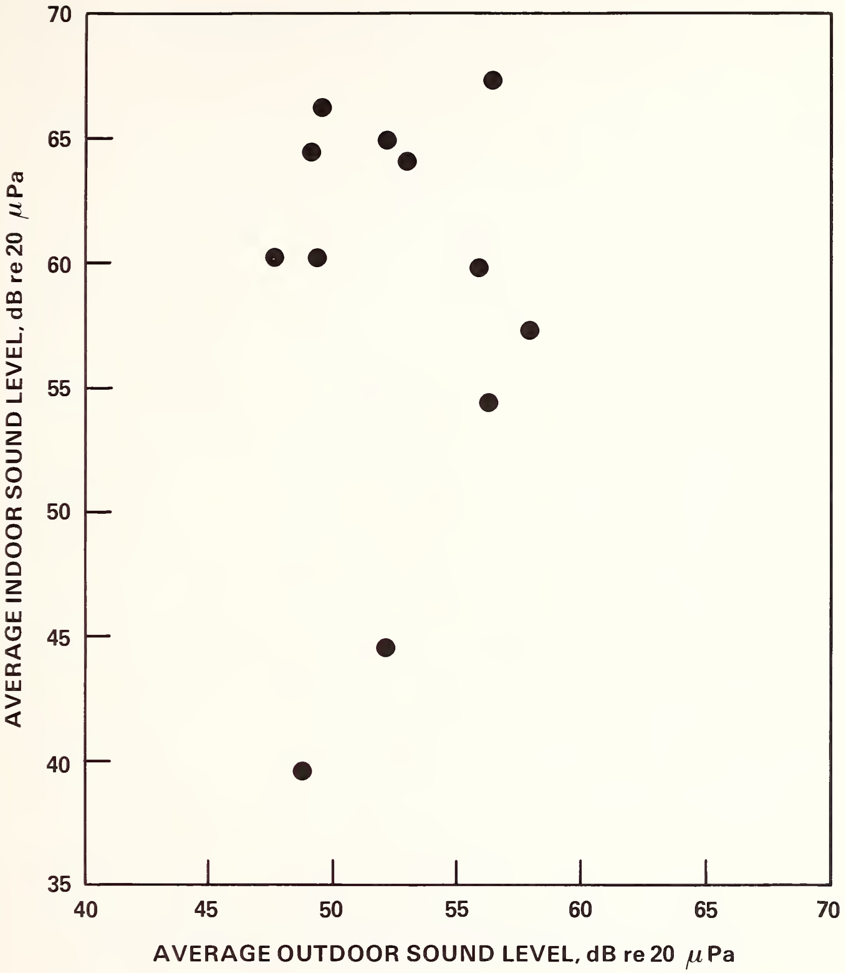

Figure 26. Evening (1900-2200 hours) indoor versus outdoor average A-weighted sound levels (L_{eq}) for twelve sites.

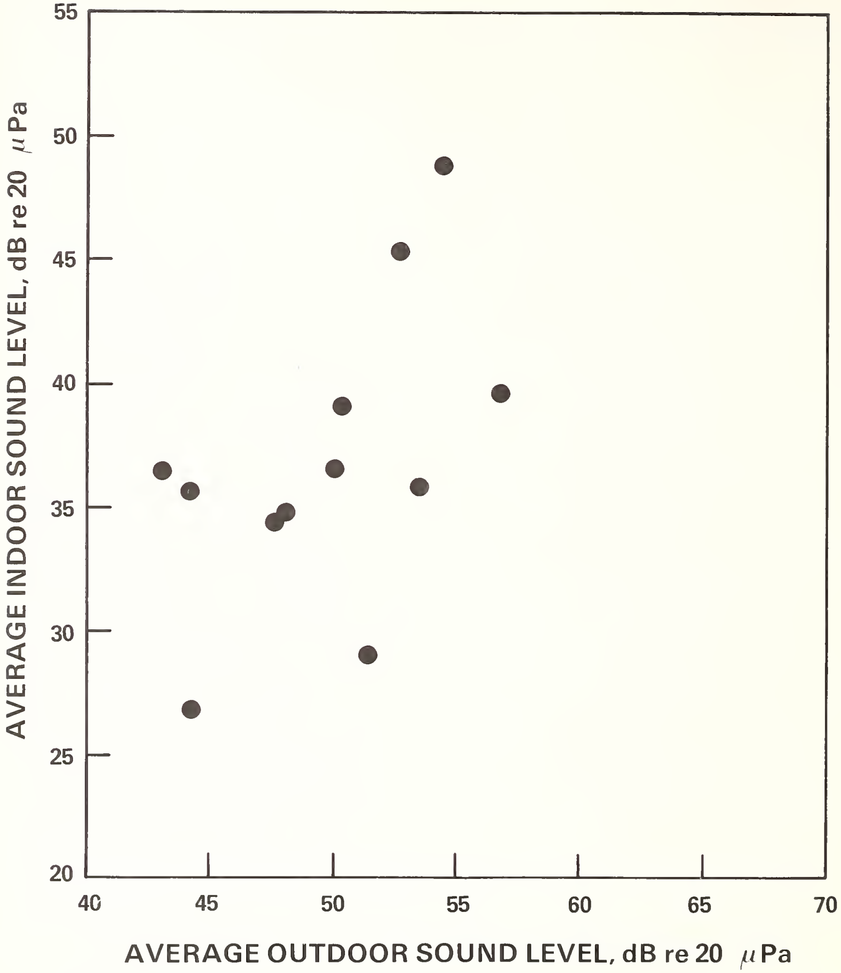

Figure 27. Late night (0100-0500 hours) indoor versus outdoor average A-weighted sound levels (L_{eq}) for twelve sites.

Table 3

Comparison of Outdoor and Indoor Sound Levels for a Set of 12 Sites Located in Urban Residential Areas Away from Major Outdoor Noise Sources.

	Time of Day				
	Daytime (0700-2200)	Nighttime (2200-0700)	Evening (1900-2300)	"Late" Night (0100-0500)	L_{dn}
Outdoors					
mean sound level, dB	58.3	51.4	57.3	49.7	59.9
standard deviation. dB	3.5	4.0	3.5	4.4	3.7
Indoors					
mean sound level. dB	58.5	47.0	58.6	36.9	59.9
standard deviation, dB	7.0	10.4	8.6	6.0	7.7
Indoor/ Outdoor Correlation Coefficient	0.1	- 0.3	0.1	0.54	- 0.2
Mean Difference between indoor and outdoor levels	+0.2	- 4.4	1.3	-12.8	0

- despite the noise isolation provided by the building structure, levels measured indoors were generally higher than those measured outdoors during the period extending from 7 a.m. to 10 p.m.;

- only during the late night hours (1 a.m. to 5 a.m.) were the indoor noise levels markedly lower than those measured outdoors (i.e., 37 dB versus 50 dB);

- at all times the indoor standard deviations about the mean significantly exceeded those observed outdoors.

The minimum indoor level occurred during the middle of the night (i.e., 0100-0500) hours, when most people sleep. This level could either be governed by intrusions from outdoors or by noise from heating and air conditioning systems. During the day and evening, when people are awake and active, the indoor sound levels (at sites away from major outdoor sources) appear to be logically due to the activities of the tenants, including speech, use of television, radios, household appliances, home tools and the like.

The large standard deviations observed for indoor noise levels during the day and evening, relative to those associated with outdoor levels, suggest that people's activities vary considerably from household to household. The observed differences are likely to depend upon the size of the families, the age of family members, socio-economic status and other sociological and psychological variables. During the course of the EPA study, no data were obtained on these factors.

The results given above must be interpreted with great caution for two reasons: first, the sample on which the data are based is very small (12 cases) and, second, this sample was drawn from a limited population of residential locations and intentionally excluded noisy areas such as those around highways and airports. Nevertheless, the data presented above suggest that in relatively quiet urban residential areas, where outdoor A-weighted Day-Night Noise Levels (L_{dn}) range from approximately 52 to 65 dB, indoor sound levels are primarily controlled by the occupants' activities. Only during the nighttime, when people were asleep, was the acoustical climate of the home possibly controlled by outdoor intrusions.

The above conclusions were based upon the use of A-weighted average sound level as the descriptor of the noise environment. It is not clear whether these conclusions would hold if a descriptor were used that is greatly influenced by variations in noise level, such as Noise Pollution Level, or if a frequency weighting were used that assigns more importance to sound at lower frequencies (which can more easily be transmitted from outside to inside).

Regardless of what descriptors are used to characterize the outdoor and indoor environments, however, indoor noise levels will also be due to both indoor and outdoor sources. The question thus arises as to how one should establish criteria for indoor noise levels and for the contributions, to indoor levels, of outdoor sources.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A review is given of existing criteria that could be applied to rating the noise environment in dwellings, to rating noise isolation between dwellings, and to rating noise isolation from outside to inside a dwelling. It is concluded that the central problem is to select appropriate criteria for rating the interior noise environment. Once this is done, criteria for noise isolation can be derived directly and these in turn can be used to derive performance requirements for building elements, such as partitions and exterior walls

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Building acoustics; building codes; isolation; noise; noise criteria; rating scheme; sound transmission.

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